



Mécanismes de rémunération de la capacité : évaluation analytique des expériences contemporaines et leçons pour la conception future des marchés de l'électricité.

Charlotte Scouflaire

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THÈSE DE DOCTORAT
DE L'UNIVERSITÉ PSL

Préparée à Université Paris Dauphine - PSL

**CAPACITY REMUNERATION MECHANISMS:
AN ASSESSMENT OF THEIR PERFORMANCE AND IMPLICATIONS FOR
MARKET DESIGN**

Soutenue par

Charlotte Scouflaire

Le 4 Décembre 2019

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L'Université Paris-Dauphine n'entend donner aucune approbation ni improbation aux opinions émises dans les thèses; ces opinions doivent être considérées comme propres à leurs auteurs.

"C'est peut-être pourquoi le monde
d'aujourd'hui commence à craquer
autour de nous. [...] Tous, sous les mots
contradictaires, nous exprimons les
mêmes élans. Nous nous divisons sur des
méthodes qui sont les fruits de nos
raisonnements, non sur les buts : ils sont
les mêmes."

Terre des Hommes, Saint Exupéry

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Mécanismes de rémunération de la capacité: évaluation analytique des expériences contemporaines et leçons pour la conception future des marchés de l'électricité

Résumé de la thèse

Les mécanismes de capacité (CRMs selon l'acronyme anglais de *Capacity Remuneration Mechanisms*) ont été développés afin de corriger les imperfections de marchés qui émergent dans le monde réel. Ces imperfections sont suspectées de diminuer l'efficacité du marché, menant, entre autres, à une quantité de capacités opérationnelles insuffisante. En effet, si le marché *Energy-Only* (EO) est unanimement considéré comme théoriquement efficace par la communauté scientifique, il est aussi de notoriété commune que les conditions nécessaires à cette efficacité ne sont pas réunies en réalité (e.g. la concurrence pure et parfaite). Pour pallier les incitations à investir jugées insuffisantes par un certain nombre d'observateurs, les CRMs accroissent la régulation du marché en spécifiant clairement un objectif de fiabilité, au risque de générer d'autres formes d'inefficacité. Cependant, peu d'études proposent une analyse de la performance empirique des différentes architectures de marché. En effet, l'absence de contrefactuel rend cette tâche complexe.

Cette thèse contribue à la littérature par une discussion à la fois quantitative et qualitative, théorique et empirique qui vient enrichir le débat sur la performance empirique des CRMs. Elle est constituée de 4 essais, chacun abordant la performance des CRMs sous un angle différent :

1. *Real World Capacity Mechanisms: Context, Dynamics and Performance* propose une identification systématique des paramètres affectant la performance des CRMs dans un cadre d'apprentissage au fil du temps.
2. *What Do Models Tell Us About Capacity Remuneration Mechanisms (CRMs)? A Literature-Based Analysis of CRMs Performance Compared to the Energy-Only Market* étudie la per-

formance des marchés avec CRM et sans (EO) dans les résultats de modélisation afin de capturer robustesse de tels résultats à différentes spécifications.

3. *Information Value in Capacity Market Designs: Public Consultations and Requirements Definition* explore les préférences des acteurs pour la précision d'un signal concernant les obligations de capacité, qui peuvent être soit *ex ante* ou bien *ex post* dans le cadre d'un marché de capacité décentralisé.
4. *Capacity Remuneration in Power Markets: An Empirical Assessment of the Costs and Benefits of Precaution* considère l'effet de la mise en œuvre d'un CRM sur les prix au consommateur final afin d'en déduire un potentiel coût net de mise en œuvre.

Introduction

L'électricité est souvent considérée comme un bien atypique parce qu'elle est difficile à stocker de manière rentable. Cette caractéristique est d'autant plus problématique que la demande est globalement inélastique, ce qui implique que l'équilibre offre-demande repose principalement sur la capacité de l'offre à s'adapter à la demande en temps réel. En effet, tout déséquilibre a des conséquences désastreuses sur la stabilité du réseau, menant au mieux à des délestages localisés, au pire à un *black out*. En ce sens, la capacité disponible doit dépasser la demande à la pointe pour éviter l'émergence de ces situations de rareté. Ainsi, lorsque le niveau de demande se rapproche du niveau de capacité disponible, cette dérive devient rare et le prix se décorrèle du coût marginal pour refléter la rareté [Boiteux, 1960]. En concurrence pure et parfaite, la rente inframarginale ainsi créée permet de recouvrir les coûts fixes et conduit à des entrées et sorties du marché optimales. En conséquence, le niveau de capacité est optimal et reflète les fondamentaux. Le corollaire de ce mode de fonctionnement est que la rentabilité des centrales dépend du niveau des pics de prix se développant sur un marché de gros déjà très volatile.

Cependant, la concurrence pure et parfaite est surtout un cadre d'analyse et les marchés sont affectés d'un certain nombre d'imperfection pouvant mener, ou non, à des défaillances de marché (déviations de l'optimum) [Newbery, 1989]. Ces défaillances de marché peuvent être classifiées en deux catégories : (i) celles générant une inefficacité du signal prix et (ii) celles créant des distorsions dans l'incitation à investir.

Le fait que les consommateurs finaux n'observent pas le niveau des prix en temps réel est la distorsion la plus évidente puisque le prix de gros, moteur des décisions d'investissement, ne reflète pas les préférences des consommateurs. En ce sens, l'égalisation du coût marginal de l'électricité avec son bénéfice marginal est improbable [Caramanis, 1982; Cramton and Ockenfels, 2012]. La méconnaissance des préférences des consommateurs rend aussi l'exercice du pouvoir de marché du côté de l'offre plus difficile à identifier. Cela conduit souvent à la mise en place d'un prix maximum sur les marchés afin d'empêcher les prix de s'envoler au-delà de la propension à payer des consommateurs [Stoft, 2002]. Si ces maximums limitent effectivement le pouvoir de marché, cela peut se révéler bénéfique. Dans le cas contraire, cela va distordre le prix [Oren, 2005] et donc les incitations à investir, générant une perte sèche. De la même manière, toute intervention hors marché visant à rééquilibrer le système aura tendance à affecter les prix [Joskow and Tirole, 2007]. À plus court terme, certains observateurs considèrent les marchés d'équilibrage comme étant inefficace, générant un sous-investissement par rapport aux besoins effectifs. En définitive, il existe plusieurs imperfections ayant un effet potentiellement distorsif sur les prix.

Cependant, même si le signal prix reflète effectivement les fondamentaux du marché, il est possible que l'incitation à investir soit malgré tout faussée. En effet, compte tenu de l'effet délétère d'un sur investissement sur les prix et du fait que les investissements s'effectuent de manière discrète (par centrale), les opérateurs ont intérêt à n'investir dans la centrale marginale que s'il n'en découle pas de sur investissement. À l'équilibre, les agents auront donc tendance à sous investir par rapport à l'optimum [Keppler, 2017]. En sus de potentiels comportements stratégiques, la logique même d'un marché EO efficient repose sur la complétude des marchés et l'absence d'aversion au risque. Deux hypothèses qui ne sont pas vérifiées dans la réalité et génèrent des équilibres

sous optimaux [de Maere d’Aertrycke et al., 2017]. Une information incomplète sur l’offre et la demande dans le futur accentue les effets précités, générant des cycles d’investissements. Ceux-ci sont d’autant plus importants que le délai entre la décision d’investissement et le début effectif de la production est long [de Vries, 2004]. En d’autres termes, l’équilibre de marché va se fixer autour de l’optimum, ne l’atteignant que par hasard [Von Der Fehr, 1994].

Sachant que l’équilibre de marché sera sous-optimal, la question que pose l’architecture de marché est de limiter la perte sèche liée aux imperfections de marché. Cela n’est cependant pas tâche aisée lorsque l’efficacité de l’incitation à investir n’est évaluable que dans des situation extrêmes et rares, donc proposant un faible nombre d’observations. Par ailleurs, compte tenu de l’hétérogénéité des systèmes, la quantification de la perte sèche réelle nécessiterait l’existence d’une situation de référence (contrefactuel). Il est ainsi difficile de trancher en faveur d’une ou l’autre architecture de marché sur la base d’arguments objectifs et quantifiés.

Cependant, certains observateurs considèrent que la sécurité d’approvisionnement possède des attributs d’externalité, créant une divergence entre l’optimum social et l’équilibre privé : les acteurs de marchés auront toujours tendance à sous investir par rapport à l’optimum social, justifiant la mise en œuvre d’un cadre légal visant à accroître l’incitation à investir afin de se rapprocher de l’optimum social : les mécanismes de capacité (CRMs). En effet, si certaines de ces imperfections peuvent être corrigées en améliorant le signal prix directement, d’autres nécessitent une intervention. Comme toute intervention, les CRMs ont un coût, au-delà des coûts de transaction inhérents à toute forme de régulation, les asymétries d’informations rendent toute réglementation sous optimale. D’après Joskow [2010], cette situation est empirée par les disruptions telles que les progrès technologique.

La littérature sur les CRMs est donc unanime sur la sous-optimalité de toute architecture de marché dans des conditions réelles. Cependant, l’absence de quantification des pertes sèches empêche la convergence des préconisations en termes d’architecture de marché. Cette thèse s’insère dans cette littérature en cherchant à évaluer empiriquement la performance des CRMs. Elle développe donc quatre chapitres abordant la question sous un angle différent, à la fois en termes de problématique et de méthodologie. Deux chapitres s’intéressent à la performance des CRMs en comparaison d’un benchmark alors que les deux autres regardent plus en détails les décisions de mise en œuvre en terme de design (voir table 1).

| Thème/Methode | Empirique | Theorique |
|--------------------|------------|------------|
| Mise en oeuvre | Chapitre 1 | Chapitre 3 |
| Coûts et bénéfices | Chapitre 4 | Chapitre 2 |

Table 1: Thèmes et méthodes des chapitres

Le premier chapitre examine le processus d’apprentissage supranational qui s’est déroulé au cours des trois dernières décennies. A travers un ensemble d’études de cas, il met en évidence les leçons tirées des réglementations passées et dévoile les éléments réglementaires qui dominent la mise en œuvre des CRMs à l’heure actuelle. Le deuxième chapitre s’intéresse aux performances respectives du marché EO et des CRMs. En passant en revue la littérature de modélisation

qui considère les deux architectures de marché, il est possible d'évaluer la performance relative des deux modèles en raisonnant en différence par rapport au modèle de référence (EO). Les hypothèses spécifiques et les imperfections éventuelles du marché incluses par les auteurs donnent un aperçu de la diversité des systèmes et des conditions d'opération des marchés. En ce sens, un résultat persistant dans tous les modèles et sous toutes les hypothèses pourra être considéré comme plus universel. Le troisième chapitre porte sur le rôle de l'incertitude dans l'élaboration de l'architecture de marché. En effet, la mise en œuvre d'un CRM nécessite la consultation d'un ensemble de parties prenantes. Plus particulièrement, ce chapitre s'intéresse un élément de design spécifique : la définition des obligations de capacité dans un mécanisme décentralisé. En effet, celles-ci peuvent être *ex ante* ou *ex post*. Le modèle théorique met en évidence les préférences des acteurs pour l'une ou l'autre conception –*ex ante* ou *ex post*– lorsque la demande agit de manière stratégique sous incertitude sur les futurs besoins en capacité. Enfin, le dernier chapitre adopte une vision plus globale du problème, en recherchant une corrélation entre la mise en œuvre de la rémunération des capacités et la modification des prix pour l'utilisateur final. En effet, la mise en œuvre de la rémunération des capacités s'accompagne de deux effets contradictoires : la composante supplémentaire du prix –augmentation des prix pour l'utilisateur final– devrait être, au moins partiellement, compensée par une réduction des prix de gros en moyenne –baisse de la facture. Cet effet n'est pas robustement différent de zéro, mais présente une faible tendance à être négatif. Ce chapitre de conclusion suggère que, dans l'hypothèse probable où les CRMs n'aggravent pas la sécurité d'approvisionnement (voir chapitre 2), une telle mesure pourrait s'avérer bénéfique pour les consommateurs finaux.

Essai 1: Real World Capacity Mechanisms: Contingency, Dynamics and Performance

Overview

Des mécanismes de rémunération de la capacité (CRMs) ont été mis en place dans le monde entier afin d'assurer la sécurité de l'approvisionnement. Un rapide coup d'œil sur les conceptions contemporaines révèle la diversité des outils dont disposent les régulateurs pour atteindre cet objectif commun. Ce constat est en opposition directe avec la littérature abondante qui souligne la prédominance de certains éléments de design par rapport à d'autres : [Mastropietro et al., 2016; Pérez-Arriaga, 2013; Pfeifenberger et al., 2009]. L'abondance de tels articles suggère un processus d'apprentissage inter-systèmes qui se serait produit au cours des dernières décennies. Cependant, la convergence des designs qui devrait en découler [Golub et al., 2010] semble n'être que partielle et la forte variance sur certains éléments est déconcertante. Convaincue que le contexte international est au moins aussi pertinent que le contexte national [Bennett, 1991; Correljé and de Vries, 2008] pour comprendre l'évolution de la conception des CRMs, je fais l'hypothèse qu'un apprentissage se produit, conduisant à une forme de convergence. Cependant, ce processus est entravé à la fois par les spécificités locales et les disruptions telles que changement technologique.

Méthodologie

Après avoir développé un cadre original pour analyser les facteurs institutionnels affectant la conception d'un CRM, je cherche des éléments empiriques pour appuyer l'hypothèse. D'une part, les choix en termes de design des CRMs s'appuient sur l'expérience observée dans d'autres systèmes ayant un CRM. D'autre part, ceux-ci s'expliquent par des facteurs exogènes ainsi que par le type d'imperfection de marché identifiée. La régulation étant un processus adaptatif, les disruptions telles que le changement technologique affectent aussi le processus. Alors que l'apprentissage suggère une convergence possible dans les choix de mise en œuvre, l'hétérogénéité résiduelle peut s'expliquer par une hétérogénéité des facteurs exogènes et des imperfections de marché. En combinant les informations disponibles dans des publications, des rapports et la littérature universitaire sur les règles du marché des capacités, j'ai recensé 27 caractéristiques clés. En effet, l'architecture des documents juridiques reflète la façon dont les caractéristiques de conception sont organisées du point de vue des organismes de réglementation, tandis que les articles universitaires insistent sur des caractéristiques particulières qui pourraient être soit dominantes, soit controversées. Les caractéristiques clés sont regroupées en 6 grandes catégories : design général, contrat (côté offre), demande de capacité, produit, marché et contribution des technologies non conventionnelles. Les mises en œuvre et les réajustements successifs dans dix systèmes ¹ conduisent à près de 20 designs différents qui peuvent être analysés dans ce cadre. Pour chacun d'entre eux, les facteurs exogènes, les motifs et les enseignements sont mis en évidence afin de comprendre les raisons de la convergence (partielle). Cela permet d'avoir une vision claire de l'évolution spatiale et géographique de la réglementation.

Résultats

Parmi les quelques 30 caractéristiques considérées, plus de la moitié sont de plus en plus choisies (c'est-à-dire convergentes) dans le design des CRMs. Le choix de caractéristiques similaires dans les designs récents reflète une efficacité supposée et suggère les choix de design qui pourraient dominer dans le futur. Ceux-ci incluent un marché centralisé à 3 ans avec un contrat d'un an qui repose sur l'obligation de produire ou d'être disponible en cas de rareté. Pour créer un produit homogène, plusieurs critères définissent explicitement la capacité éligible et des *deratings* sont appliquées à la capacité installée. Les pénalités de non-conformité sont proportionnelles au prix de marché et des règles limitant le pouvoir de marché sont incluses dans le design. En ce qui concerne la demande, une courbe à pente descendante est basée sur le coût net des nouvelles entrées. Le marché s'équilibre en amont de l'année de livraison (3-4 ans) mais des enchères d'ajustement sont prévues pour tenir compte d'éventuelles erreurs de prévision.

Le rythme d'adoption de ces caractéristiques au cours du temps, met l'accent sur trois grandes périodes d'apprentissage. (i) Les premières expériences ont été menées dans les années 90, ce qui a donné lieu à la mise en œuvre d'un large éventail de modèles conceptuels différents, tous relativement simples en comparaison avec les réglementations actuelles. (ii) Tirant les leçons des succès et identifiant des points d'amélioration, les années 2000 présentent déjà des formes de convergence, mais soulignent aussi l'importance de caractéristiques spécifiques. Cela conduit à

¹PJM, ISO-NE, MISO, NYISO, Royaume-Uni, France, Espagne, Irlande, Italie et Colombie

une complexification des réglementations avec un intérêt particulier accordé au signal prix, aux obligations et au pouvoir de marché. (iii) Bien que la convergence soit plus évidente dans les années 2010, l'évolution technologique apparaît comme un choc exogène, perturbant le processus de convergence et forçant à nouveau l'innovation réglementaire.

Conclusion

En utilisant un cadre d'analyse inspiré par les théories de l'apprentissage social (*social learning*), les facteurs institutionnels affectant le design des CRMs sont étudiés. Les facteurs exogènes et les défaillances de marché identifiées définissent la pertinence des caractéristiques considérées pour le design d'un CRM. En outre, les changements technologiques et les retours d'expérience observés dans d'autres systèmes vont affecter directement la hiérarchisation des caractéristiques restantes (considérées comme pertinentes). Les objectifs politiques et l'avis des parties prenantes ont une incidence sur le design final. Par conséquent, les années 90 ont été caractérisées par un large éventail de conceptions. Même si certaines fonctionnalités mises en œuvre ont fini par être abandonnées, cela a permis aux acteurs d'apprendre de leurs erreurs. En effet, les solutions proposées dans les années 2000 pour corriger ces défauts suggèrent déjà une forme de convergence. Ce phénomène s'est encore accentué dans les années 2010, soutenant l'hypothèse de l'apprentissage social : les caractéristiques les plus efficaces ont été de plus en plus adoptées. Cela permet de découvrir le design probable des CRMs dans le futur. Cependant, l'existence de spécificités locales empêche les designs de converger pleinement. En outre, le lobby croissant pour la valorisation des nouvelles technologies et le verdissement du mix de production entraîne de nouveaux défis pour le régulateur en termes d'évaluation de la fiabilité et d'incitation à la performance. En ce sens, si les années 2010 présentent de nouveaux signes de convergence, elles montrent aussi des signes de disruption. L'évolution du design des CRMs suggère l'obsolescence progressive de la taxonomie habituelle à mesure que les catégories usuellement utilisées deviennent poreuses.

Essai 2: What Do Models Tell Us About Capacity Remuneration Mechanisms? A Literature-Based Analysis of CRMs Performance Compared to the Energy-Only Market

Overview

Bien que le marché EO soit l'équilibre de premier rang théorique, de nombreux acteurs estiment que les imperfections du marché génèrent un biais structurel vers le sous-approvisionnement et qu'une intervention est nécessaire pour rétablir l'optimalité (ou du moins s'en rapprocher). Différents designs ont été adaptés afin de créer une valeur intrinsèque à la sécurité d'approvisionnement (SoS). Une fois valorisée de manière explicite, la sécurité d'approvisionnement devrait être à la fois accrue et stabilisée. En conséquence, la rareté devrait être moins répandue sur le marché de l'électricité – au moins dans la plupart des CRMs –, réduisant ainsi la volatilité et le niveau des prix. Le surplus du consommateur pourrait alors être affecté dans n'importe quelle direction. L'ampleur de ces effets dépend directement des imperfections de marché.

Malheureusement, la performance relative des CRMs par rapport au marché EO reste empirique-

ment peu évaluée. La grande diversité des CRMs mis en œuvre ainsi que les caractéristiques intrinsèques de chaque système empêchent l'émergence de recommandations politiques claires. Cependant, la littérature de modélisation qui s'est développée au cours des dernières décennies contribue largement à la discussion en comparant les marchés avec et sans CRM selon des hypothèses données. Considérées conjointement, ces études donnent un aperçu des conditions dans lesquelles un marché doté d'un CRM pourrait surpasser un marché EO : les résultats de ce dernier servent de point de référence pour normaliser les conclusions. Bien qu'elle ne puisse remplacer une évaluation de la performance empirique des CRMs, cette analyse de littérature ciblée éclaire sur la performance relative des deux architectures de marché en fonction d'imperfections et d'hypothèses données. Plus précisément, elle conclut sur la robustesse des résultats aux choix de représentation faits par les auteurs et met en évidence les éléments consensuels ainsi que les facteurs de divergence.

Méthodologie

Cette analyse tente de synthétiser l'abondante littérature modélisant les CRMs en cherchant à savoir si une amélioration des conditions d'investissement et du surplus du consommateur peut être défendue. Le principal critère de sélection a donc été l'existence de résultats à la fois pour le marché EO et les marchés avec CRM. Le premier étant généralement considéré comme l'équilibre de premier rang (sous les hypothèses de concurrence pure et parfaite), il sert de référence. Ainsi, la conclusion de chaque article est rapportée à une norme similaire : la performance des CRMs est évaluée en différence avec le marché EO. Les conclusions concernant les principales préoccupations de la littérature sont utilisées comme indicateur de performance : la sécurité de l'approvisionnement, le surplus du consommateur, la volatilité des prix et les cycles d'investissement. Pour tenir compte des choix de modélisation et facilement identifier d'éventuels facteurs de divergence, les études sont classées en fonction du type de modèle utilisé et de l'incertitude, mais aussi du ou des types de CRM inclus dans l'analyse.

Résultats

En accord avec les hypothèses formulées, la vingtaine d'études analysées ne convergent pas vers une conclusion simple : les résultats dépendent des imperfections de marché considérées (marché EO efficient ou défaillant). De façon surprenante, les paradigmes de modélisation orientent la question de recherche mais ont peu d'impact sur les conclusions. En effet, l'ensemble des articles concluent qu'une architecture de marché avec un CRM conduit à une réduction de la volatilité des prix et des cycles d'investissement par rapport à un marché EO. En revanche, moins d'un tiers des études considérées abordent ces sujets, le consensus sur ces questions limitant leur intérêt pour les auteurs. Au contraire, la sécurité d'approvisionnement est presque systématiquement discutée dans les articles et les CRMs s'avèrent améliorer celle-ci dans la plupart des cas, au risque de potentiellement sur-investir. Ainsi, les améliorations en termes d'investissement ne sont pas toujours associées à une augmentation du surplus du consommateur. Contre toute attente, ce ne sont pas les choix de modélisation qui génèrent ces différences dans les résultats : les débats préexistants sur le surplus du consommateur d'électricité expliquent la plupart des disparités : l'énergie non fournie (le rationnement) n'est pas systématiquement valorisée et lorsqu'elle l'est,

sa valeur (VoLL) reste non consensuelle.

Conclusion

Les quatre éléments caractérisent le plus souvent la performance des CRMs dans le débat académique et public sont analysés. Ce chapitre fait la synthèse des principales conclusions de la littérature utilisant des modèles et souligne les points pour lesquels les désaccords persistent. La plupart des études du panel s'accordent sur l'efficacité des CRMs pour réduire à la fois la volatilité des prix et les cycles d'investissement par rapport au marché EO. En ce qui concerne la sécurité d'approvisionnement et le surplus du consommateur, les effets sont globalement bénéfiques bien que moins consensuels, principalement en raison de la définition hétérogène de la sécurité d'approvisionnement (valorisation des délestages versus coût du sur investissement) et du surplus. En général, la littérature gagnerait en clarté si les discussions critiques sur ces définitions étaient plus systématiques.

Essai 3: Information Value in Capacity Market Designs: Public Consultations and Requirements Definition

Overview

Les marchés de capacité, un type particulier de CRM, sont conçus pour internaliser la sécurité d'approvisionnement lorsque l'autorité publique considère que le marché de l'énergie n'incite pas suffisamment à l'investissement. Elle intervient pour compléter les revenus des centrales qui pourraient être insuffisamment rentables et pourtant précieuses pour la stabilité du système. Dans le présent chapitre, nous examinons les préférences en matière de précision de l'information lorsque celle-ci est considérée comme inhérente à la conception des mécanismes de capacité. Sur les marchés de capacité décentralisés, les besoins de capacité peuvent être définis soit *ex post*, soit *ex ante*. Le premier cas implique que la prévision des besoins totaux de capacité, information fournie par l'autorité publique, ne donne qu'une information incomplète ou imprécise aux acteurs du marché. En effet, l'obligation réelle dépend de la réalisation de la demande électrique, et non des prévisions, laissant une forte part d'incertitude. C'est le cas en France où la réalisation effective du marché affecte leur obligation et où les détaillants sont pénalisés pour leurs erreurs de prévision. Dans le cas d'une définition des obligations *ex ante*, l'information publique révèle parfaitement le niveau des obligations individuelles de capacité. Les acteurs sont obligés à hauteur de l'information qui leur est fournie par l'autorité publique. Ainsi, les acteurs du marché ne sont pas pénalisés en cas d'insuffisance sur l'année de livraison (comme dans l'ancien PJM ou l'ancien MISO).

La définition de l'obligation *ex post* introduit donc un forme d'incertitude sur le niveau futur de la demande de capacité par rapport à une obligation *ex ante*. En essayant de comprendre les préférences des acteurs concernés (acheteurs de capacité –LSEs– ou vendeurs de capacité) en ce qui concerne la définition des obligations, nous adaptons et généralisons un modèle de Roy et al. [2019] et décrivons les LSE comme des agents stratégiques qui se font une concurrence à la Cournot. Nous étudions l'effet des différents niveaux de concurrence et de précision de

l'information (niveaux d'exigences) sur les préférences des acteurs telles qu'elles sont exprimées, par exemple, lors des consultations publiques. Les préférences des acteurs (surplus du consommateur, maximisation du profit et préférence majoritaire parmi les propriétaires de capacité) sont ensuite comparées aux résultats de maximisation du bien-être. Bien que le pouvoir de marché des acheteurs (oligopsonie) augmente la probabilité que l'ensemble des acteurs préfèrent une information précise (obligation définie *ex ante*), cette situation existe aussi en concurrence parfaite. En outre, la préférence majoritaire des propriétaires de capacité n'est pas nécessairement alignée avec celle qui maximise le profit agrégé. Les préférences exprimées lors de consultations publiques étant des préférences individuelles, l'autorité publique doit les analyser avec précaution lorsque les agents sont hétérogènes (comme l'offre dans le modèle). Par ailleurs, il est possible que le surplus social soit maximal avec une information imprécise en présence de pouvoir de marché.

Méthodologie

Alors que les marchés de capacité sont caractérisés par des agents hétérogènes et des comportements stratégiques dans la réalité, nous posons deux grandes hypothèses simplificatrices pour étudier l'effet de la définition des obligations en capacité dans un marché décentralisé. Dans le modèle que nous analysons, (i) la demande est constituée de n consommateurs homogènes qui représentent les acheteurs de capacités, ou acteurs obligés, dont la demande est linéaire. (ii) Les fournisseurs de capacité sont atomiques et fournissent leur capacité dans le cadre d'une courbe d'offre continue. En adaptant et généralisant un modèle de Roy et al. [2019], nous discutons le design préféré des acteurs –*ex ante* vs. *ex post*– dans le cadre d'un marché de capacité décentralisé avec une concurrence imparfaite en quantité (Cournot) du côté de la demande. Celle-ci est obligée d'acheter de la capacité avec une incertitude sur le niveau de sa demande future. L'ensemble des acteurs reçoit un signal public sur l'état du monde le plus probable (consentement à payer élevé ou faible). L'information fournie est inégalement instructive en fonction du design choisi (*ex ante* ou *ex post*). Les préférences des acteurs en termes de précision du signal sont respectivement caractérisées en considérant : le surplus social, le surplus agrégé des acheteurs de capacité, le profit agrégé des propriétaires de capacité et le profit individuel des propriétaires de capacité (critère de la préférence majoritaire).

Par construction, le modèle considère que la définition des besoins est la seule caractéristique pertinente du design : tous les autres paramètres de l'architecture de marché sont connus et implicitement pris en compte dans le coût d'opportunité des acheteurs de capacité. Une étude de cas basée sur des données historiques du marché allemand de l'électricité est ensuite construite pour simuler les résultats avec différentes courbes de demande de capacité en fonction du degré de concurrence, du coût d'opportunité et des prévisions de besoins. A la connaissance des auteurs, il s'agit de la première contribution appliquée au sein de la littérature sur *Bayesian Persuasion*.

Résultats

Les fonctions objectifs des acteurs sont non monotones en matière de précision de l'information : il existe des seuils distincts pour le niveau souhaité de précision de l'information. Ceux-ci dépendent d'un certain nombre de paramètres qui définissent la forme relative de la courbe de demande et de la courbe d'offre. Lorsque les acheteurs sont en concurrence pure et parfaite, le résultat

est simple : la détermination des besoins *ex ante* maximise toujours le surplus social. Sous certaines conditions, l'ensemble des acteurs peut préférer cette situation. En cas de concurrence imparfaite entre les acheteurs de capacité, l'information devient de plus en plus précieuse pour les acheteurs à mesure que le pouvoir de marché augmente. Cela implique que les situations où tous les acteurs préfèrent une information précise deviennent plus probables (conditions moins limitantes) à mesure que la concurrence diminue. Toutes choses égales par ailleurs, la forme de la courbe d'offre autour de l'équilibre est le principal moteur des préférences en termes de précision de l'information. Par exemple, une précision plus faible –définition de l'obligation *ex post*– pourrait être préférée par les acheteurs ou les propriétaires de capacité lorsque la forme de la courbe d'offre change. La pente de la courbe de la demande (coût d'opportunité) ainsi que le niveau de concurrence entre les acheteurs (acteurs obligés) ont de forts effets redistributifs et peuvent, dans certains cas, affecter les préférences. En d'autres termes, les résultats du modèle indiquent les conditions en termes de concurrence, de demande et d'offre sous lesquelles certaines catégories d'agents, voire tous préfèrent un haut degré de précision informationnelle (définition de l'obligation *ex ante*). Cependant, l'accord de tous les acteurs sur un signal imprécis (définition de l'obligation *ex post*) est impossible : il y a toujours au moins un type d'agent qui favorisera une information parfaite.

De plus, nos résultats montrent dans quelles conditions la majorité des propriétaires (hétérogènes) est en désaccord avec le critère de maximisation de profit afin d'éclairer sur les situations où les consultations publiques ne fourniraient pas l'information voulue. L'étude de cas donne un exemple de ce résultat préjudiciable. L'étude de cas suggère qu'une information précise concernant la capacité requise maximise toujours le bien-être d'un point de vue statique (c'est-à-dire sans entrée). Toutefois, en extrapolant les résultats théoriques, une détermination *ex post* des besoins pourrait être préférable vis à vis du surplus social lorsqu'il y a un besoin d'investissement, et donc que la courbe d'offre est localement très pentue autour de l'équilibre en raison de nouveaux entrants plus chers que les capacités existantes. Bien que cela soit théoriquement possible, les cas où la majorité des fournisseurs de capacité choisissent un niveau de précision différent de celui qui maximiserait le surplus global sont très peu probables.

Conclusion

Dans un marché de capacité décentralisée à terme (*forward*), l'information (prévisions) sur la demande (obligations) des différents acteurs obligés est une question cruciale. L'autorité publique doit donc décider si la maximisation du surplus social viendrait plutôt d'un design où la prévision du besoin de capacité est directement contraignante pour les acteurs (exigences *ex ante*) ou s'il est préférable d'indexer le niveau d'obligation (la demande de capacité) sur la réalisation de l'équilibre sur le marché de l'électricité (exigences *ex post*). Nous analysons un marché de capacité décentralisé où des acheteurs homogènes (acteurs obligés) sont des agents maximisant leur surplus qui adoptent un comportement stratégique dans un contexte d'incertitude quant à leur future demande. Des propriétaires de capacité hétérogènes participent au marché en offrant leur valorisation de la capacité. L'accumulation de leurs offres forment une courbe d'offre ascendante. Comme l'information fournie par l'autorité publique réduit l'incertitude d'une part, mais peut aussi diminuer les achats de capacité de précaution par les acteurs obligés d'autre part,

nous recherchons le niveau de précision d'information préféré. Nous soulignons les préférences en termes de précision de l'information pour chaque groupe d'acteurs : les acheteurs, les propriétaires de capacité à la fois conjointement et individuellement ainsi que le design qui maximise le surplus social.

Suivant l'intuition économique, les résultats montrent que l'information complète est le plus souvent préférée. Néanmoins, le modèle met en évidence les désaccords possibles entre les acheteurs de capacité et les propriétaires de capacité, étant donné les forts effets redistributifs de la précision de l'information fournie par l'autorité publique. En outre, les propriétaires de capacité ayant des valorisations différentes de la capacité, ils peuvent avoir des préférences individuelles différentes en ce qui concerne la précision de l'information fournie. Dans ce cas, le vote à la majorité (qui peut être imaginé comme un processus de consultation publique) peut ne pas converger avec le degré de précision qui maximiserait les profits et le bien-être général. L'application numérique indique que cette situation est empiriquement peu probable : de tels désaccords entre les fournisseurs de capacité sont limités à une période de transition – forme locale de la courbe d'offre – entre une situation où tous les acteurs préfèrent une information précise et un désaccord entre les acheteurs et les vendeurs en ce qui concerne la conception préférée.

Essai 4: Capacity Remuneration in Power Markets: An Empirical Assessment of the Cost of Precaution

Overview

En raison d'un certain nombre de défaillances, il est souvent considéré que le marché EO assure difficilement un niveau adéquat de sécurité d'approvisionnement. Ainsi, les mécanismes de capacités (CRMs) sont mis en œuvre à titre de précaution lorsque le régulateur s'attend à ce que la marge de réserve soit trop faible, mettant en danger la sécurité d'approvisionnement. Ces mécanismes visent à assurer un niveau de capacité aussi optimal que possible. Les centrales sont alors payées pour leur disponibilité en plus de leur production ; les CRMs considèrent donc la sécurité d'approvisionnement comme un bien distinct de l'électricité.

En l'absence de mesure précise des pertes sèches générées par les différentes architectures de marché, la décision de mettre en place un CRM peut être considérée comme une précaution. Celle-ci serait prise sur la base d'hypothèses formulées par le régulateur concernant la fiabilité optimale et l'effet du risque sur les décisions d'investissement. Il est donc légitime de s'interroger sur le coût de cette précaution pour les agents concernés lorsque l'on n'est pas en mesure de quantifier le biais réel causé par les imperfections de marché. À l'aide d'une régression économétrique inter-systèmes, le coût financier net de l'architecture de marché est analysé, mesurant le différentiel de prix au consommateur final avec et sans CRM. En effet, si les différents coûts de système sont empiriquement difficiles à mesurer, ils sont répercutés sur les consommateurs finaux en totalité. En regardant la variation des prix auxquels ils sont confrontés, il est possible d'avoir une vision sur l'effet conditionnel net de la mise en œuvre d'un CRM (de la réduction des prix de gros combinée à la composante additionnelle de la sécurité d'approvisionnement).

Méthodologie

En utilisant un panel de données concernant 25 états (états américains et pays européens) sur une période de 24 ans, la dynamique des prix de l'énergie pour l'utilisateur final industriel est analysée pour établir l'effet conditionnel net de la mise en œuvre d'un CRM. Le modèle économétrique tient compte des effets individuels et des facteurs de hausse des prix de l'électricité propres à chaque État en contrôlant le mix de production et les prix du gaz. Il prend en compte la variation moyenne des prix réels pour l'utilisateur final à la suite d'un changement d'architecture de marché (incluant un CRM). Comme l'impact de la mise en œuvre d'un CRM n'est pas forcément instantané, notamment en raison de l'inertie des prix aux consommateurs finaux, des variables retardées sont aussi introduites. Tenant compte de la diversité des CRMs, une variable réglementaire supplémentaire est introduite pour indiquer si le design en place comprend une période *forward*. Lorsque cette période existe, elle permet aux investisseurs de disposer d'informations supplémentaires sur les conditions futures du marché par rapport à un mécanisme à court terme. Cela devrait induire une dynamique différente sur le marché [Pfeifenberger et al., 2009]. En outre, les résultats sont aussi étudiés au niveau régional non seulement au travers d'effets fixes temporels différenciés pour les USA et l'UE, mais aussi plus directement avec des régressions séparées. En complément, des régressions de robustesse sont également effectuées dans des panels et des modèles ajustés.

Résultats

Les coefficients des variables de contrôle de la composition de l'électricité et des prix du gaz sont plutôt conformes à la dynamique prévue du marché. En ce qui concerne la mise en œuvre du CRM, les utilisateurs finaux industriels ne sont pas significativement affectés dans un sens ou dans l'autre à la suite d'un changement d'architecture de marché vers un CRM – ou le changement pour une période *forward* –, que ce soit sur le panel complet ou sur le sous-panel européen. En revanche, les mécanismes de capacité aux États-Unis sont significativement associés à une baisse moyenne de 1,1 % des prix de l'énergie pour les utilisateurs finaux industriels. Bien que les utilisateurs finaux industriels bénéficient généralement d'un plus grand pouvoir de négociation que les utilisateurs finaux résidentiels, on constate que les CRMs tendent à réduire l'écart entre les prix des deux catégories d'agents.

Conclusion

Bien que les CRMs soient souvent critiqués pour leur coût, les résultats de ce chapitre indiquent que leur mise en œuvre n'augmente pas de manière significative la facture des consommateurs industriels. Au contraire, le sous-panel américain suggère même une faible incidence négative (conditionnelle) sur les prix suite au changement d'architecture de marché vers un CRM. Il est notable que la plupart des CRMs récemment mis en œuvre comprennent une période *forward*, indiquant qu'il s'agirait potentiellement d'une caractéristique Pareto-améliorante. Toutefois, les résultats n'indiquent pas de réduction des prix lors de la mise en œuvre de cette caractéristique par rapport à d'autres mécanismes de capacité à plus courts termes. Cela peut s'expliquer par le nombre limité d'observations.

Par ailleurs, il faut faire preuve de prudence à la lecture des résultats car les CRMs sont généralement mis en œuvre dans le cadre de réformes plus vastes. Les résultats ne peuvent donc pas isoler complètement l'effet de telles réformes. Enfin, le coût de la précaution pourrait en réalité être négatif plutôt que positif comme souvent argumenté dans le débat public. Pour discuter plus en profondeur les effets d'une telle réforme, il est utile d'évaluer les gains de sécurité d'approvisionnement résultant de la mise en œuvre afin de pouvoir conclure sur l'efficacité réelle du mécanisme. Quoiqu'il en soit, l'absence d'effet marqué donne à penser que le design des CRMs (les caractéristiques choisies) a une incidence considérable sur l'efficacité globale de ceux-ci. Cela ouvre la voie à une étude plus approfondie du coût net de la mise en œuvre.

Conclusion générale

Dans un contexte où la théorie économique soutient que les CRMs peuvent être équivalents entre eux et optimaux sous certaines hypothèses, ce travail de recherche vise à comprendre leur performance empirique. En effet, ces hypothèses ne sont pas nécessairement vérifiées en réalité, d'où l'importance d'étudier le rôle des caractéristiques de design choisi. Dans le chapitre 1, il est intéressant de noter comment la diversité des choix réglementaires en termes de mise en œuvre de CRMs dans les années 1990 contraste avec la similitude imperfections dont ont souffert ces premiers designs. En effet, la diversité des choix initiaux en matière de design reflète le poids de facteurs exogènes dans l'élaboration des politiques, et ce d'autant plus en l'absence d'apprentissage. Cependant, la similitude des imperfections générés par ces designs (volatilité des prix, pouvoir de marché, faible incitation à la disponibilité etc) entraîne des solutions réglementaires similaires, créant ainsi une forme de convergence partielle des designs. Cette observation abonde dans le sens d'un apprentissage supranational : le design des CRMs s'est continuellement amélioré depuis les premières mises en œuvre dans les années 1990. D'après l'analyse de CRMs existants, ceux-ci semblent principalement découler de croyances et d'anticipations concernant l'efficacité relative du marché EO par rapport aux CRMs. En effet, le débat sur la supériorité de l'une ou l'autre des architectures de marché n'est pas réglé d'un point de vue empirique. En effet, seul un cadre contrôlé permet d'avoir une idée précise des avantages et des inconvénients des deux modèles et c'est l'objet du chapitre 2.

La littérature de modélisation donne une image de diversité dans les croyances et anticipations par la diversité des hypothèses utilisées. Dans cette littérature, le marché EO est aussi parfois utilisé comme point de référence pour donner de la perspective aux résultats, ce qui les rend aussi comparables. En ce sens, des résultats convergeant sur l'ensemble des études indique une certaine robustesse de ce résultat. Ainsi, les CRMs semblent effectivement réduire à la fois la volatilité des prix et les cycles d'investissement par rapport au marché EO, et ce, sous un grand nombre d'hypothèses et d'imperfections de marché différentes. Par ailleurs, la littérature suggère aussi que la mise en œuvre d'un CRM aura tendance à améliorer la sécurité d'approvisionnement bien que quelques papiers soient plus nuancés. Toutefois, l'effet sur le surplus du consommateur n'est pas établi fermement puisqu'une amélioration de la sécurité d'approvisionnement peut signifier une réduction du nombre de défaillances néfastes ou au contraire un sur investissement coûteux. Les cas où la sécurité d'approvisionnement n'est pas clairement améliorée par la mise en œuvre

d'un CRM sont caractérisés par un marché EO efficace. Ainsi, l'effet sur le surplus ne découle pas directement de l'équilibre mais plutôt du prisme de la définition du surplus qui est utilisé. En ce sens, ce sont moins les hypothèses ou les modèles utilisés qui vont affecter les conclusions de la littérature, mais bien des divergences dans les notions et les définitions : le type du modèle utilisé n'affecte pas les conclusions. En d'autres termes, l'existence d'un CRM ne détermine pas à elle seule la performance du marché. Pour bien comprendre le besoin d'un CRM et son efficacité, il faut le replacer dans le contexte plus large de l'architecture globale du marché et des objectifs politiques ou économiques (e.g. quelle définition du surplus utiliser).

Dans un contexte changeant caractérisé par une forte hétérogénéité entre les systèmes, les expériences passées sont imparfaitement instructives sur le design qui s'avèrera le plus performant. C'est pourquoi des consultations publiques sont utilisées pour obtenir des informations de la part des acteurs du marché, et réduire l'asymétrie d'information dont souffre l'autorité publique. Récemment, un grand nombre de systèmes ont opté pour un marché centralisé – abandonnant les anciens CRM décentralisés avec des exigences *ex ante*. Dans ce contexte, le choix de la France –décentralisée avec des exigences *ex post*– soulève des questions sur raisons d'un tel choix. RTE [2014] fait valoir que les exigences *ex post* incitent davantage les consommateurs à exprimer leurs choix et à prendre leurs responsabilités en matière de sécurité d'approvisionnement. Une conséquence moins discutée des exigences *ex post* est le déplacement du risque vers la demande et l'émergence potentielle d'un pouvoir de marché, alors même que le secteur de l'électricité est déjà caractérisé par d'importantes possibilités de comportement stratégique.

En évaluant cette possibilité dans un modèle d'oligopsonne de Cournot où les acteurs du marché expriment leurs préférences concernant la définition des obligations, le chapitre 2 montre que les obligations définies *ex ante* sont principalement préférées. Par ailleurs, les obligations *ex ante* peuvent, sous certaines conditions, maximiser le bien-être de l'ensemble des parties prenantes, cette préférence augmente avec le coût d'opportunité du sous-approvisionnement et diminue avec la concurrence. Cela explique potentiellement la tendance générale à mettre en œuvre des conceptions avec des exigences *ex ante*. En revanche, les obligations *ex post* ne sont jamais préférées unanimement et lorsqu'elles accroissent le surplus global, cela se fait toujours au détriment des acheteurs dont le pouvoir de marché se trouve limité par une information imprécise. En ce sens, il apparaît clairement que le choix de définition des obligations *ex post* ou *ex ante* possède un fort pouvoir redistributif. En outre, le papier discute la fonction objectif de l'autorité publique en insistant sur le concept de votre majoritaire comme exemple de critère de décision pour l'une ou l'autre des définitions de l'obligation. Le modèle permet aussi de discuter la fourniture centralisée de capacité (monopsonne bénévole) en l'approximant par la situation de concurrence pure et parfaite. Dans ce cas, les obligations *ex ante* vont toujours maximiser le surplus global.

Finalement, les résultats des chapitre 1, 2 et 3 sont confirmés par le chapitre 4. L'hypothèse selon laquelle la variété des contextes de mise en œuvre affecte grandement la performance des CRMs est confortée par l'absence d'effet conditionnel significatif entre la mise en œuvre d'un CRM et les prix pour l'utilisateur final. En effet, l'étude se concentre sur la période 1991-2014 et raisonne en effet moyen. Bien que la théorie économique suggère que tous les CRMs puissent avoir des effets similaires sous certaines conditions, il est peu probable que celles-ci soient vérifiées en réalité, spécialement sur la majeure partie de la période considérée qui était caractérisée par

une grande variance dans les choix de design. Malgré cela, les résultats suggèrent que les prix pour l'utilisateur final pourraient diminuer légèrement après la mise en œuvre des CRMs (cas des Etats-Unis).

Ainsi, compte tenu de la convergence récente des conceptions tant sur le marché de l'électricité que sur celui des capacités, cette analyse pourrait gagner à être reproduite dans les années à venir pour inclure les CRMs nouvellement mis en œuvre en Europe. En effet, l'idéal d'un marché commun en Europe a réduit la variance des conceptions nationales, créant un environnement plus favorable à l'évaluation statistique. S'ils se confirment, ces résultats viendraient largement nuancer le débat public actuel. En effet, celui-ci considère généralement les CRMs comme un mécanisme coûteux, avec un effet limité sur le prix l'énergie ainsi que le coût de financement des investissements. Dans ce contexte, il s'agit souvent de savoir si ces coûts sont justifiés. Cependant, si l'amélioration de la sécurité d'approvisionnement grâce à un CRM est avérée (comme le suggère le chapitre 2), et que le mécanisme a un coût négligeable voire négatif, la question se pose différemment et une précaution (ou assurance) qui serait gratuite mériterait d'être envisagée sérieusement.

Ces quatre chapitres reflètent donc l'origine du désaccord entre les défenseurs du marché EO et les partisans des CRMs. En effet, leur performance relative est contextuelle, et l'hétérogénéité des systèmes ainsi que des choix de design rendent difficile une conclusion empirique claire. Toutefois, les enseignements tirés des 30 dernières années et la convergence partielle des designs qui en résulte pourraient permettre de tirer des conclusions plus objectives dans les années à venir. Sans se prononcer en faveur de l'imperfection des marchés ou de la réglementation, cette thèse expose les limites de la recherche d'une réponse (trop) simple. En effet, une telle quête est freinée non seulement par l'hétérogénéité des systèmes et des réglementations, mais aussi par l'inertie du processus d'apprentissage. Par ailleurs, les résultats théoriques sont difficilement généralisables en raison de la complexité des interactions de la vie réelle par rapport aux possibilités de modélisation. Attaquant le problème de la performance des CRMs sous plusieurs angles, cette thèse contribue à identifier les limites de l'évaluation empirique tout en apportant des éléments de réponse.

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Introduction

Capacity remuneration mechanisms (CRMs) result from the political will to find a regulatory solution to the question of adequacy in liberalized electricity markets. Standard economic theory maintains that market outcomes are optimal –under a set of assumptions–, rendering intervention and regulation unnecessary in a well-functioning market. The motivation for CRM implementation thus lies in market imperfections. In addition to the identification of market imperfections, a quantification of the resulting inefficiencies is necessary to justify intervention (i.e., make sure it is welfare improving) [Newbery, 1989]. Because precise estimation of the induced bias has not been successfully performed yet, there is a constant doubt on whether liberalized markets can induce enough investments [Bublitz et al., 2019] –and ensure adequate security of supply (SoS). In this context, the preference for one market design or another does not result from a perfectly informed cost-benefit analysis, but rather the application of a precautionary principle: deviations from the theoretical first best case, which motivate the implementation of CRMs, are based on the hypothesis that the costs of putting SoS at risk are higher than the costs of securing the reserve margin.

The notion of security of electric supply (SoS) is essential to any electricity market design. Indeed, inhabitants and economic sectors of Europe and the Americas have become used to a continuous supply of electricity, making any shortage unpopular. As a matter of fact, those would probably be acceptable if the whole economy had not lost its ability to cope with outages. Where people used to own candles and flashlights, they now rely upon their cellphone for lightening during outages; frozen food has replaced the custom of limiting stocks of perishable food: the increasing reliance on electrical appliances makes outages every time more costly due to the absence of planned alternatives. The unpredictability of outages worsens this lack of adaptability. As highlighted by Keppler [2017], advanced information about possible shortages could drastically reduce the costs of such power interruption. SoS is all the more important that outages are largely unpredictable. The elevator example is quite illustrative: an unforeseen outage might take the passengers of an elevator by surprise, keeping them trapped for a while. If they had been able to foresee the outage, they would simply have taken the stairs and used the outage time for more productive activities than waiting. Indeed, limited storage capabilities and the need to maintain the stability of the electricity grid require supply and demand to be balanced at any point in time. Along with modest demand responsiveness, this creates conditions for a relatively inelastic demand in the short run (except under conditions of involuntary load-shedding). The adjustment during normal operating hours thus needs to be provided by supply by varying the utilisation rate of a given generating capacity. Inelasticity is problematic as it is the inability to respond to price

signal: no matter how high the price is, no additional electricity can be produced nor is demand willing to renounce consumption, mainly because it does not receive such price signal [Cramton and Stoft, 2005]. In this context, investments will be sub-optimal [Caramanis, 1982]. In addition, any curtailment would be performed independently from preferences where minimizing the cost of an outage would require to select the consumers with the lower willingness-to-pay [Joskow and Tirole, 2007].

Rather than trying to resume the debate on the need for CRMs and justify their implementation, this study considers the implementation of CRMs as a precaution and takes existing regulations as given without questioning the choices made. Indeed, regulation-making is a long haul process where little is left to chance. If the principle of precaution is a sound reason for intervention, it does not absolve from performance assessment. This issue is increasingly being tackled in the literature, especially after some decades of implementation worldwide. Contributing with this respect, this introductory chapter presents the challenges of CRMs' performance assessment. In turn, this doctoral thesis is organized around two main research questions: chapters one and three explore the design process of CRMs while chapters two and four investigate the empirical performance and the cost of CRMs in correcting potential market imperfections.

Section 1 defines some key concepts and puts forward potential market imperfections that could endanger capacity adequacy. In the absence of precise assessment of the relative benefits of intervention compared to the EOM actual performance in real-life, section 2 presents why CRMs can be considered as a precaution. In this context, the first concern of this study is not to address whether CRMs are actually needed², but rather if they meet expectations i.e., ensure capacity adequacy at a limited cost. Further, section 2 succinctly presents the various forms of CRMs. Linking the potential market imperfections to the different modes of intervention –CRM taxonomy– as in table 2, suggests the decisive role of regulation-making and implementation details in tailoring investment incentives. This is the second concern of this introduction: what drives the choice towards specific design features? In this sense, this doctoral thesis aims at a better understanding of the intervention process and its consequences. It investigates the performance of CRMs in four different chapters of which two investigate the performance of CRMs compared to the alternative market designs given existing market imperfections while the remaining two deal with regulation-making and implementation choices. Section 3 introduces the main challenges with this respect and develops the research questions addressed in the four chapters of this study and the main results. Ultimately, section 4 presents the structure of this doctoral thesis and provide a succinct summary of each of the upcoming chapters

1 Energy-only markets and empirical inefficiencies

1.1 Definitions

Security of supply (SoS) being both challenging and desirable –to some extent–, it is necessary to define what it refers to precisely. The different causes of outages relate to specific time horizons.

²With this respect, Hogan [2005] argues for improving the EOM design while Cramton and Stoft [2005] find CRMs necessary but unlikely to be fully efficient.

Batlle and Pérez-Arriaga [2008] identify four separate notions of SoS. (i) *Security* concerns the short-term issues of network services and lies out of the scope of this study. (ii) *Firmness* refers to the efficient operation of plants, including fuel provision, maintenance schedule, etc. (iii) *Adequacy* relates to the longer-term problem of having enough available capacity to meet future demand. Thus, it mainly deals with entry and exit in the market. (iv) Ultimately, the *Strategic expansion policy* deals with the very long-term issue of securing primary energy supply. For instance, the development of nuclear power in France fits in this category as the objective was to limit the dependency on fuel imports [Léautier, 2019]. This last component is also mainly disregarded in this study for being more of geopolitical concern.

In terms of SoS, the four components are necessary, but the risks associated with each of them are different. This study investigates capacity remuneration; as such, it focuses on investment incentives and mainly refers to adequacy-related SoS (see section 1.2 and 1.3). The issue of adequacy would be easily solved if the demand was predictable. However, estimating the adequate level of capacity necessary to meet peak demand, when said demand is both uncertain and unresponsive to price signal remains an unsolved issue up to now. This issue is called "operation paradigm" in Oren [2005]. He additionally identifies technological and political barriers that prevent treating adequacy as a private good. Mainly, this would require the development of real-time metering and consumer empowerment. As those obstacles have not been fully overcome yet, adequacy – also referred to using the broader term "security of supply (SoS)"³ – will be considered as having externalities attributes in the remainder of this study.

1.2 Energy-only market and pricing inefficiencies

Since liberalization, power pools have been created all over the world to develop competitive trading of electricity. Indeed, competitive markets are known to be efficient under the usual set of hypotheses of the first fundamental theorem of welfare economics, i.e., the invisible hand theorem. This section briefly discusses the functioning of an efficient electricity market, the so-called energy-only market (EOM) [Stoft, 2002; Oren, 2005]. It then moves to the market imperfections potentially creating pricing inefficiencies. As discussed in the previous section, those refer to different time horizons but this study disregards the security issue as defined by Batlle and co-authors. In this sense, a simplifying assumption is often made in this work: when the other dimensions of SoS are secured, efficient real-time balance of markets will always be possible. The very short-term issue of network balance and subsequent balancing and ancillary services are mostly left aside to focus on the energy market.

In an EOM, the market of reference is the day-ahead market, where electricity is traded on an hourly basis. Numerous scholars, such as Oren [2005] and Léautier [2019], find useful to refer to Boiteux [1960] to explain the functioning of electricity prices: two types of pricing naturally emerge in the market, periods with or without scarcity. During the latter, marginal pricing is predominant: all units offer their energy at their marginal cost, and the infra-marginal rent serves for fixed costs recovery. However, the infra-marginal rent of the most expensive units is unlikely to be sufficient due to their limited running-hours. This is why, when at full usage of

³Although it is formally an abuse of language, "reliability" might also be used to describe a similar concept.

all available generation capacities scarcity pricing is triggered to ensure full cost recovery for all units participating in the market. The few hours of scarcity, where prices explode, are thus crucial for the full cost recovery of those peaking units, which are themselves essential for the SoS. This is true, to a lower extent, for other operators. Efficient scarcity pricing would then fix the clearing price up to the value of lost load (VoLL)⁴. Under perfect competition, the resulting equilibrium is efficient, and the scarcity rent triggers investments. Indeed, a high number of scarcity hours generates positive profits that foster entry in the market. On the contrary, the absence of scarcity deters entry and also renders the most expensive units unprofitable, inciting exit –decommissioning– from the market. Through entry and exit, the level of the scarcity rent theoretically stabilizes at its optimal level, so does installed capacity.

Unfortunately, real-life markets never meet the assumptions of perfect competition, meaning that equilibrium outcomes are bound to be inefficient to some extent. In turn, the distorted price signal might twist investment incentives and put SoS at risk. The first step to assess how important the issue is, is the identification of the potential sources of market failure⁵ –market imperfections. The second step, which will be discussed later, is determining the actual size of the resulting inefficiency to deduce the soundness of intervention.

The most obvious market imperfection lies in the isolation of consumers from the price signal. This *de facto* inelasticity is problematic: the characterization of the demand on the energy market then generates significant price volatility while imperfectly representing the consumers' preferences. Indeed, even the VoLL is defined as an "average value" due to a lack of better metrics [Cramton et al., 2013]. This makes the main equilibrium conditions, the equalization of the marginal cost of electricity with its marginal value, unlikely [Caramanis, 1982; Cramton and Ockenfels, 2012]. The uncertainty around the demand-side preferences also makes market power abuse from the supply-side more complex to identify. Suspensions of market power are often resolved through the implementation of a price cap which prevents scarcity prices from rising too high [Stoft, 2002]. The residual question is whether price caps limit the market power or a legitimate scarcity rent⁶ [Oren, 2005]. The former situation is rather welfare-improving while the latter might put the SoS at risk, creating the so-called "missing money"⁷.

Two additional possible distortions in the price signal come from the necessity of instant supply and demand equalization. As any imbalance might put the whole grid at risk, system operators either need to adjust supply, or demand. Concerning the former, adjusting supply is, to

⁴The Value of Lost Load is defined as the average value placed by end consumers on losing power in an average rolling blackout by Cramton et al. [2013]. Oren [2005] uses a similar definition. Besides, it should be noted that the VoLL is difficult to estimate and probably nonlinear as well. SoS is also valued at the margin by the cost of new capacity since the willingness to pay for additional capacity and the cost of new capacity are equal at equilibrium.

⁵A market failure refers to a situation where market imperfections generate inefficiencies i.e. a deviation from the Pareto efficient situation or equivalently a deadweight loss. I refer to market imperfections as the potential sources of market failure.

⁶Cramton et al. [2013] actually considers that scarcity periods are market failures: prices during these periods do not represent the meeting of supply and demand. An argument that tends to justify price caps.

⁷Hogan [2005] defines the missing money as the foregone revenue due to market intervention –e.g. price caps. Complementarily, a slightly more restrictive definition only includes the foregone revenues necessary to restore the profitability of the least cost generation portfolio [Joskow and Tirole, 2007].

some extent, doable on a market basis through balancing or ancillary services. Although, we generally make the assumption that those markets effectively ensure short-term SoS, imperfect valuation of those services is sometimes pointed out as a source of under-investment in conventional technologies –especially flexible ones. In addition, brown-outs are sometimes performed to maintain grid stability to deal with inadequate investments. Such interventions distort investment incentives by artificially reducing demand –curtailing–, and thus the realized scarcity on the market [Joskow and Tirole, 2007]. In this sense, the supply-side is plagued with missing flexibility markets which generate missing money either directly or indirectly.

All in all, the price signal in energy markets imperfectly carries information about the actual scarcity on the market due to captive consumers, interventions and missing markets. This probably results in inefficient investment levels. This is all the more improbable considering that accurate price signal does not necessarily lead to optimal investment. Indeed, agents’ and more specifically, investors’ preferences are affected by other factors. Possible distortions with this respect are discussed in the following section.

1.3 Energy-only market and distortions in investment incentives

Market outcomes might also be affected by potential distortions in investment incentives, even when scarcity is accurately reflected in the price signal. For instance, a structural imperfection in investment incentives has been highlighted by Cramton and Ockenfels [2012]: when capacity is adequate –i.e., the demand can be satisfied at all times– then scarcity disappears. Since the scarcity rent is necessary for cost recovery, the most expensive units then exit the market first due to insufficient profitability expectations. Following this reasoning, the market will never provide enough capacity to meet the demand in any circumstances since the marginal unit does not recover its costs in such a situation.

This tendency for under-investment is amplified by the rational expectations of investors and market power. This is well phrased by Von Der Fehr [1994]: "Optimal spot prices only lead to efficient investment under the assumption that firms ignore the effects of their capacity decisions on spot prices". Indeed, any investment will improve SoS; the consequent reduction in scarcity will reduce the rent available for fixed costs recovery. In this sense, it is in the best interest of all generators and investors to maintain an inadequate level of capacity and benefit from the scarcity rent. Standard economic theory would states that as long as the profit is positive, investments will take place up to the optimal level. However, as Keppler [2017] argues, those asymmetric incentives in the context of lumpy investments not only render optimality improbable, but it also fosters cautious behavior from the investors. In other words, avoiding as much as possible over-capacity means under-shooting the optimal level.

The good news is that being able to supply demand under any circumstances has never actually been the objective. Indeed, securing capacity against any possible level of demand is extremely costly due to the occurrence of extreme and rare events. This is why most countries have defined a reliability target expressed in loss of load expectations (LoLE)⁸. However, those represent

⁸The North American Electric Reliability corporation (NERC) defines the LOLE "as the expected number of days per time period (usually a year) for which the available generation capacity is insufficient to serve the

administratively set targets and Cramton and Stoft [2006] consider that the reliability targets in effect worldwide are actually too high –too expensive– compared to consumers’ preferences.

In this sense, scarcity events are bound to happen in the market; they will only be more and more constrained as the reliability objective is high. For instance, a 3h/ year LoLE –as in France– means that the most expensive plants only have 3h –in expectations– of actual scarcity to recover the totality of its costs. This implies two things: (i) the prices are bound to be extremely high during those hours and (ii) such peaking units *need* to be available at that moment. In this sense, the uncertainty on annual gross profits is increasing in marginal costs [Olsina et al., 2014] because investors refrain from investing in capital intensive technologies –which typically have lower marginal costs.

In a world free of risk-aversion with complete hedging possibilities, the market is workable in this configuration. However, real-world markets do not meet these assumptions and both risk and risk-aversion distort investment incentives [de Maere d’Aertrycke et al., 2017]. Imperfect information on future supply and demand functions further alters investment decisions. Installed capacity then displays a cyclical pattern which is exacerbated by the time lag previous to commissioning [de Vries, 2004]. In other words, market equilibrium will err around optimality and real life situations are likely to be characterized by some degree of inefficiency as suggested by Von Der Fehr [1994].

As a summary, section 1.2 has highlighted the reasons why the price signal might not reflect scarcity. In turn, section 1.3 has shown that even when the price signal actually carries market information, it might not lead to adequate investments (see table 2). To complexify the picture at hand, imperfections interact with one another. For instance, the lower the number of scarcity hours, the more impact a price cap has on revenues –since peaking units only have a reduced number of hours to recover their fixed costs, they need very high prices. The entanglement of potential market imperfections probably explains the limited results on the relative efficiency of the different market designs [Bublitz et al., 2019]. This is unfortunate because supposed sub-optimal investment does not inform on the magnitude of the imperfection. As such, it does not, *per se*, justifies a market intervention [Newbery, 1989]. Indeed, no market is actually perfect, and intervention is only desirable if it can reduce the size of the inefficiency.

2 Capacity remuneration mechanisms

2.1 Dealing with market imperfections: CRMs as a precaution

The debate on capacity remuneration is lead by disagreeing views on whether there is a need for market intervention at all. As suggested in the previous sections, the actual level of SoS is challenging to assess for relying on extreme and rare events realization. Per definition, those are tail events about which little is known. The optimal level of SoS is also hardly known due to the

demand at least once per day." see https://www.nerc.com/comm/PC/Documents/2.d_Probabilistic_Adequacy_and_Measures_Report_Final.pdf accessed on August 3rd, 2019. While for RTE (the French system operator); it is rather "the period during which, in a given year, the power system is exposed to a risk of insufficient supply, irrespective of the magnitude of the potential deficit". For example, France aims for 3h/year while the PJM targets a one-day-in-ten-years LOLE.

unresponsiveness of end consumers. The market imperfections discussed earlier only complete the list of difficulties in the precise estimation of the deadweight loss.

In this sense, the best explanation for CRM implementation is precaution: CRMs are implemented as a precaution because the –economic, social and political– costs of blackouts are too high. Such a discrepancy between the willingness-to-pay –as expressed on the market– and the actual cost of a black-out implies externality attributes⁹. The example of the elevator described earlier is only one among many. However, the reasons to implement CRMs all present the same flaw: they lie on the *assumption* that the difference between the social and the private equilibrium is significant. More specifically, deviations from optimality are expected to be important enough to justify an intervention –to correct identified market imperfections.

| Market imperfection | Solution | CRM |
|--|--|--|
| Captive consumers | ✓Empowerment (ex: real-time pricing, prosumers etc) | - |
| Interventions (price cap, brown outs) | ✓Improve pricing | - |
| Missing markets for services | ✓Improve pricing | - |
| Missing money | ✓Allow for scarcity in the market | SR |
| | ✓Complete revenues | All CRMs |
| Risk-aversion / lack of hedging | ✓Reduce risk on the market to lower the need for hedging | CM, CP, RO |
| | ✓Improve hedging possibilities | RO and CfD |
| Asymmetric incentives / strategic under-investment | ✓Fix a target | CM, RO, SR |
| Imperfect information (investment cycles) | ✓Increase transparency | CM, RO (forward clearing and/or long term) |
| Externality | ✓Create property rights (Coase) | Volume-based CRMs |
| | ✓Intervention (Pigou) | Price-based CRMs |

SR: Strategic reserve, CM: Capacity market, CP: Capacity payment, RO: Reliability option

Table 2: Market imperfections and potential solutions

The detailed description of market imperfections is useful for our purpose, not because they *justify* market intervention, but because they *explain* it. Indeed, market interventions are tailored to correct the market imperfections considered as prevalent [Joskow, 2010]. Table 2 summarizes the market imperfections from section 1 (first column) and the solutions usually prescribed by economic theory (second column). Part of them does not require effective intervention as improving the market itself should improve the situation. For instance, consumer empowerment is a step towards demand-side responsiveness: improving the price signal could reduce inefficiencies

⁹See Keppler [2017] and Salies et al. [2007] for a thorough discussion on the characterization of SoS as an externality, a private or a public good.

where the market design itself is responsible for such deviations, as with price caps or missing markets for flexibility. This is the position of the European commission in the *Clean Energy for All Europeans* package: "The market must also provide the right incentives for consumers to become more active and to contribute to keeping the electricity system stable.[...] The proposed measures also contain measures that ensure that state interventions designed to make sure there is sufficient energy available are only used when needed, and in a way that does not distort the internal electricity market."¹⁰. As suggested in this quote, improving markets should, but might not be sufficient to ensure SoS. This is because the remainder of market imperfections could require more direct intervention from the public authority. For instance, the missing money can be reduced either by increasing scarcity pricing or by compensating for those foregone revenues. Similarly, a reduction of market risk naturally reduces the impact of risk-aversion and the need for hedging in the market. As discussed, objectives in terms of SoS are often legally defined, making them binding as a way to fight under-investment. Ultimately, the internalization of externalities falls within a broad literature, most successfully represented by Pigou [1920]; Coase [1960] and Weitzman [1974]. It is those five last market imperfections that are addressed by capacity remuneration (see table 2).

Capacity remuneration mechanisms (CRMs) gather a broad range of regulatory tools aiming at ensuring SoS under the hypothesis that the market is unable to do so. As the terminology suggests, they always tackle the missing money problem as well as its potential externality, mainly through the explicit valuation of SoS. Appart from the strategic reserve (see the following section for a broader discussion on the relative attribute of each type of design), the CRMs tailored often deal with risk-related issues and asymmetric incentives. In this sense, the type of intervention (CRM) chosen is likely to reflect the concerns regarding market imperfections. The purpose of the following section is to link one of the standard taxonomies to those market imperfections as in the third column of table 2.

2.2 CRMs: a taxonomy

The previous sections have discussed why CRMs might be implemented; this section is concerned with the modes of intervention, i.e., the types of CRMs that are implemented. The taxonomy(ies) at use in the literature has little evolved over the past 30 years [Henriot and Glachant, 2013; Meulman and Méray, 2012; CIGRE, 2016; Bublitz et al., 2019; Batlle et al., 2007]. Most CRMs can be fit into one of the four common categories: strategic reserves (SR), capacity payments (CP), capacity markets (CM), and reliability options (RO). Initially, the two main discriminating characteristics of those CRMs were the type of intervention (e.g., price or volume-based) and the reach of the measure (e.g. targeted or market-wide). This manner of characterizing designs mainly reflects the insights from general economic theory on externalities. This dichotomous view of CRM designs has lost part of its foundation: none of the currently implemented design can be characterized as purely price or volume-based. This will be further discussed in chapter 1. In addition, technical and environmental restrictions restrict the scope of any market, questioning the notion of "market-wide". This is why the focus has shifted towards the structure of incentives

¹⁰See the press release on http://europa.eu/rapid/press-release_IP-19-1836_en.htm, accessed on July 25th, 2019.

and market actors¹¹.

For instance, the CIGRE [2016]'s taxonomy mentions the type of product, requirement definition, and responsibilities with respect to procurement. This shift in approaches to the taxonomy reflects the change in concerns from high-level features to actors' strategic behaviors and potential free-riding problems. In other words, where the issue used to be focused exclusively on investments, it has now spread onto *firminess* to some extent. The sole fact that the capacity exists does not ensure its efficient operation; additional incentives are required. In this sense, CRMs now seek to avoid the "money for nothing" problem [Mastropietro et al., 2015] by ensuring that capacity is not only invested in but also available when needed. This requires tackling two additional issues: (i) the identification of scarcity periods and (ii) the definition of efficient operation. This task has proven to be quite challenging and will be further discussed in the first chapter of this dissertation. With this respect, Hogan [2017] warns that "in trying to restore missing money they [CRMs] create a new problem: misallocated money, that is, overcompensating some resources and under compensating others" and defends the improvement of scarcity pricing through the implementation of an operating reserve demand curve (ORDC) as in Texas. Although it mostly falls out of the scope of this study, it is increasingly discussed as an alternative to CRMs. It is an illustration of this evolution in stakeholders' concerns.

Strategic Reserves

The strategic reserve (SR) seeks to generate the least distortion possible in the energy market by securing additional capacity out-of-the-market. In exchange for entering the reserve, units are remunerated on a cost-recovery-basis and renounce participating in the market. In this sense, when scarcity occurs, energy prices rise –supposedly– as in an EOM. However, the subsequent risk of shortage is reduced since those units act as a buffer for the system: they will produce out-of-the-market only when SoS is at risk. Per construction, the SR mainly attracts old plants on the hedge of decommissioning; the energy market still provides the investment incentives.

The strategic reserve presents the advantage of being easily combined with pre-existing markets, but since investments still rely on the energy price signal, it requires careful design to make sure such a signal is not distorted. Mainly, SRs are often activated by a strike price –or physical shortage–, which acts as a *de facto* price cap. Indeed, as soon as the reserve is activated, scarcity disappears: a strike price too low –or too strict physical trigger– will distort the scarcity rent. In this sense, the "missing money" problem is solved through allowing scarcity in the market –but not shortages. It also secures a given reserve margin by explicitly seeking to procure the difference between market outcomes and the reliability objective. In this sense, it reduces investments cycles by mainly fighting the "low phase". Indeed, strategic reserves provide limited additional information with respect to the supply and demand functions. Even though the SR was designed to supplement the energy market without distorting it, it could cap the market price. As such, it could also effectively reduce market risk. This is a recurrent discussion when considering and comparing CRMs: outcomes vary depending on the parameters chosen.

¹¹Although this is the approach chosen in this introduction, references to the "common taxonomy" might appear later in this analysis.

Strategic reserves will be little discussed in the present study for different reasons. The main one is that it is not supposed to change the structure of the investment incentives nor the market risk –although it has the ability to do so. In this way, it is very different from other types of CRMs which create an additional, more stable source of revenue.

Capacity Markets

Historically, capacity markets (CM) were created as volume-based mechanisms –as opposed to the price-based capacity payments¹². The idea of CM is to fix the quantity required to meet the reliability target. In practice, a demand curve is increasingly used to reduce price volatility. In capacity markets, capacity is bought on behalf of end consumers, either by the load-serving-entities (LSEs) or by the system operator (SO). This is to remain so as long as consumers are captive. The actual level of remuneration is then a market outcome. In this sense, it creates a separate revenue that replaces (partially) the scarcity rent. In exchange, it is commonly required that units be available during scarcity to avoid the "money for nothing" problem described in Mastropietro et al. [2015].

For being allocated on a market-basis, this capacity remuneration should solve the missing money problem: units are expected to bid at least their missing money. Besides, capacity markets fix the quantity, or at least a range of acceptable levels of capacity, which limits strategic under-investment. If the delivery period is longer than the energy market time span, it also reduces the need for hedging –or provides a form of hedging. Including a forward period increases information disclosure as existing, as well as planned units, commit into being available in a given time frame. It forces coordination and provides information on the future supply function. The resulting improvement in investors' expectations is likely to reduce the size of investment cycles¹³.

Purposely, this definition of capacity markets is broad enough to include both centralized and decentralized procurements, which should yield similar results under perfect competition. With this respect, Bublitz et al. [2019] use separate groups. Besides, short-term as well as long-term –forward– CM are gathered in this category for often having similar designs. However, their effect on market risk is distinct: the longer the contract duration, the more stable and foreseeable the revenue. The counter-part is a higher uncertainty on capacity needs. This group also brings together different types of requirement definition that generate separate categories in other taxonomies such as CIGRE [2016] (*ex ante*, *ex post* or self-defined). In addition, CM cannot be considered as pure quantity-based mechanisms anymore, considering that current versions include an elastic demand, which, per definition, result from a price-quantity arbitrage. Considerations on implementation features will be further discussed in chapter 1.

¹²The two designs are theoretically similar [Weitzman, 1974], and are increasingly converging (see chapter 1). In addition, both consider SoS as a separate good from energy, with a price of its own.

¹³However, this is done at the expense of accurate forecast of capacity needs, which might as well generate inefficiencies. This trade off will be further discussed in chapter 1.

Reliability Options

Reliability options (RO) are hedging instruments, known in finance as one-sided contracts-for-differences or call options. Conceptually, capacity units commit into providing electricity when the reference price rises above a pre-defined strike price. In this situation, they have to pay back the difference between the market price and the strike price to the holder of the reliability option. The strike price acts as a price cap if all the capacity is committed: the contract price compensates the foregone scarcity rent. On the contrary, the units free from reliability options can cash in more than the strike price, collecting a more significant but more volatile scarcity rent. Reliability options are procured on a market-basis, most often through centralized auctions.

Reliability options thus create an additional source of revenue that can tackle the "missing money" problem. For being a hedging instrument, it is a rather long-term scheme that reduces price volatility in exchange of a fixed remuneration. As such, it limits the impact of risk on investment decisions. Besides, it defines a target to meet a reliability objective; strategic under-investment is reduced, and units are remunerated for their contribution to adequacy. As most reliability options include a forward period, the amplitude of investment cycles is likely to be reduced thanks to the additional information available.

As it might have occurred to the reader, the functioning of the reliability option is very similar to the one of a capacity market with a price cap [Cepeda and Finon, 2011; Léautier, 2016]. As a matter of fact, Bublitz et al. [2019] gather them in a single category. Its limits are thus common to all *de facto* or *de jure* capped markets: the level of the cap is determinant for its efficiency.

Capacity Payments

Capacity payments (CP) are the price-based counterpart of capacity markets. In this scheme, the public authority decides of the level of the remuneration –price– and leaves the quantity to be a market outcome. Not to fall too far from the reliability objective, the remuneration is commonly calibrated based on the expected missing money. Trying to avoid the "money for nothing" problem, they often come with the obligation to be available at scarcity.

Through this additional source of remuneration, CPs seek to tackle the "missing money" problem. It also makes units profitability less dependant on the scarcity rent, reducing possible risk-related investment distortions (section 1.3). Again, the prevalence of this effect increases with the duration of the delivery period. One of the significant advantages of CPs is to effectively control the budget allocated to SoS, making sure that the cost of the measure does not out pass the estimated willingness-to-pay.

Under this apparent simplicity, CP can grow rather complicated, including several price components so to develop diverse incentives (e.g., to invest, to be available at scarcity, etc.). With this respect, Batlle et al. [2007] suggests that the 1997 capacity payments in Spain could transit towards reliability options with the right design and incentives, suggesting strong similarities btw CP and RO as well.

Contracts-for-differences

Contracts-for-differences (CfDs) consist of long-term agreements where both parties agree on a strike price which will represent the *de facto* trading price of the two counterparts. Indeed, every time the reference price falls below the strike price, the buyer pays back the difference to the seller. On the contrary, if the reference price is above the strike price, it is the seller that reimburses the difference between the two. In this sense, CfDs are two-sided hedging instruments where volatility is canceled out for both sides. Their advantages are twofold (table 2): (i) there is no missing money since a generator will only agree on a CfD if the strike price ensures full cost recovery, (ii) it isolates the parties against market price volatility (risk).

Although CfD is a generic financial instrument, they are also used in electricity markets to stimulate a specific type of investment. They are often granted through tenders and target capital intensive technologies. Even though CfDs are not designed for adequacy purpose, they do contribute to SoS by way of fostering (targeted) investments. This is probably why they are not considered in CIGRE [2016] but would fit into the "tender for new capacity" in Bublitz et al. [2019]. In this sense, they can represent a partial solution to strategic under-investment –combined with other tools. With this respect, the British example is illustrative: CfDs are granted to low carbon technologies through tenders^a, but being successful in such a scheme prevents qualification as a capacity unit. The two schemes are thus complementary within the market design in place in the UK^b.

^a<https://www.emrsettlement.co.uk/about-emr/contracts-for-difference/> accessed on July 30th, 2019.

^bIn this study, the United Kingdom (UK) –the country– and Great Britain (GB) –the island– are used indifferently although they formally represent distinct geographic areas. As a matter of fact, GB would be the correct appellation since Northern Ireland is part of the Single Electricity Market along with Ireland.

Although this is not the purpose of this dissertation, it is worth mentioning that various criticisms on CRMs arise as well. Mainly, market equilibrium with a CRM is not more likely to be optimal than in an EOM since the public authority is not omniscient: reliability targets are calculated based on simplistic calculations and arbitrary VoLL levels [Oren, 2005]. This is problematic since deviations from the optimal capacity procurement/reserve margin distort the price signal in the electricity market. For instance, the over-procurement of capacity depresses the energy prices, sometimes below the marginal cost of the involved units¹⁴. Besides, both the EOM and CRMs are prone to gaming [Newbery, 1998; Teirilä, 2017], further limiting the probability of an optimal equilibrium in either market design.

¹⁴See the case of Spain in chapter 1 as an example of how this could happen.

3 Relevance of the study and main findings : Real-world challenges in performance assessment

3.1 Heterogeneity

The most crucial challenge preventing an accurate assessment of CRMs performance is the prevalent heterogeneity between systems. Indeed, each system faces different levels of market imperfections depending on its inherent characteristics. This creates two joint problems: (i) the need for precaution is unevenly experienced in the different system –be it objectively or subjectively– and (ii) the lessons from one system cannot be directly extrapolated to the others. In this sense, empirical case studies focusing on one system provide information of limited usefulness for other systems. On the contrary, models require a parametrization that is unlikely to reflect the complexity of real-life conditions. While the first approach is necessary to fine-tune the design, the second provides complementary information as it attempts to quantify the market imperfections and assess the need for intervention. Performance assessment is thus a complicated task.

For instance, scholars sometimes justify CRMs by the increased renewable energy source (RES) integration. Indeed, renewable generation creates additional challenges by increasing the volatility and unpredictability of the residual demand. However, most Latin American countries deal with it thanks to sufficient reservoir capacity. What generates inefficiencies in one system, might not do so in another. In this sense, quantifying the link between potential market imperfections and inefficiencies needs to be done in a broad range of settings.

With a rather qualitative approach, chapter 1 depicts past and existing CRMs in ten systems. Over time, designs grow in complexity, but also gain in similarities, suggesting the occurrence of a learning process despite heterogeneity. To better capture convergence, key design features are identified and classified as being either converging features or scattered ones. The pace of adoption of the converging features informs on the learning process. In addition, describing heterogeneity as a combination of exogenous factors and motives for CRM implementation sets out the factors of divergence in regulatory choices. For those features whose high variance in adoption forms cannot be explained in a static view –heterogeneity–, it is hypothesized that they are prevented from converging by exogenous shocks such as technological change. This framework of analysis identifies the learning channels as well as the features concerned. The increasing adoption of converging features, after the occurrence of three learning cycles already suggests that those correspond to recognized "best practices". On the contrary, the scattered features are likely to be tailored to specific systems. In this sense, chapter 1 not only identifies learning cycles, but it also provides policymakers with a starting kit to single out the unsettled issues concerning CRM design.

Where chapter 1 seeks to derive lessons from past and present real life CRMs, chapter 2 intends to summarize conclusions from the modeling literature. Indeed, models are often perceived as a "black box", a criticism that undermines the reach of their conclusions. This limit can be partially overcome by checking the robustness of such results to specification –e.g., parameters, model type, uncertainty. Through selecting papers from the modeling literature that compare a market with a CRM to an EOM benchmark, it is possible to normalize their results by reasoning in deviations

from the benchmark. Roughly twenty studies are analyzed; they mostly reflect on four market outcomes: SoS, consumer surplus (or end-user prices), price volatility, and investment cycles. Indeed, price volatility and investment cycles regard the performance of the considered CRM in correcting risk-related and strategic under-investment. If the papers analyzed are representative of this stream of literature, there is a global agreement that CRMs effectively reduce market risk and the inefficiency of investment cycles. Less straightforward is the actual effect on investment and surpluses: knowing whether CRMs actually improve SoS is the heart of the matter, but if the (captive) consumer's surplus is not improved in doing so, it is of little interest. With this respect, the analysis is less conclusive. There is a tendency for concluding that CRMs do improve SoS. However, the valuation of consumers' well being is rather an unsettled issue; driving models results in any direction depending on its characterization.

In this sense, the two first chapters contribute to two complementary streams of literature to set out when heterogeneity should and should not be seen as an obstacle to the generalization of current knowledge. Capitalizing on existing modeling studies, chapter 2 investigates the performance of CRMs compared to EOM market designs. More specifically, the robustness of conclusions over papers using different specifications suggests that CRMs might be successful in correcting a broad range of market imperfections. Complementarily, the first chapter mixes case studies and social learning aspects, highlighting the evolution of CRM designs –and subsequent lessons– over the past 30 years. In the process, the importance of design features in CRM efficiency is revealed, and a set of features that might not be affected by system heterogeneity –converging features– are identified. Those two chapters pave the way to the next ones by emphasizing the role of design features and the unsettled effect of CRMs on consumers' surplus.

3.2 Role of design features

Taxonomies are useful to understand how CRMs modify the actors' expectations: it already suggests how implementation features drive investment incentives. However, they mainly abstract from real-world conditions. Setting aside SR for being conceptually different from its counterparts, CRM categories have become porous over time due to the increasing adoption of "efficient" features (e.g., sloped demand curve, performance incentives, explicit penalties cf chapter 1). The growing attention paid to the fine tuning of designs explains the coexistence of numerous taxonomies. For instance, a CP and a CM with the same time horizon are more likely to generate similar results than two CP (resp. CM) of different contract duration. More importantly, chapter 1 has identified several channels affecting regulation-making. Mainly, two categories of agents are involved: the public authority's representatives –who make the final decision– and the other stakeholders. Where the objective of the former is often common knowledge for being legally defined, stakeholders' views are not easily derived. Public consultations are organized to collect their preferences with respect to regulation change. This is one of the motivations for chapter 3. A second motivation is the relative discrepancy between the identified converging features and some design features chosen in France.

Often described as a decentralized capacity market in the literature, the French design actually displays at least one key novel feature compared to its precursors (e.g., former MISO, former PJM): the level of capacity requirements is only known with certainty *after* the delivery pe-

riod. This *ex post* definition of capacity requirements takes away the relative hedging from which LSEs and end consumers benefit in *ex ante* requirements. Where a benevolent centralized procurement locks the reliability target up, decentralized CRMs allow for strategic behavior on the demand-side (LSEs). This situation is complexified by the uncertainty on the level of requirements generated by their *ex post* definition. Investigating conditions for each category of stakeholders to prefer such a configuration, chapter 3 sets up a Cournot Oligopsony model where homogeneous buyers seek to procure capacity under uncertainty on the level of their own demand –which depends on the future state of the world. Explaining why requirements are most often defined *ex ante*, results show that all actors might agree towards such a design. However, market participants would never prefer *ex post* requirements all at once: additional information always improves the situation of at least one of them. This result brings a new light on some regulatory decisions. Indeed, a given design feature can be preferred most of the time by most of the stakeholders and yet, not be chosen because specific market conditions incite the public authority to prefer alternative solution.

3.3 Difficulty of net cost assessment

As discussed in section 2, CRMs are mainly seen as a precaution in this analysis. This approach is all the more justified considering the lack of consensus regarding the effect of CRMs on consumers' surplus (chapter 2), even though this is partially due to discordant views on the private and social benefits of increased SoS. Because the consumer surplus is affected negatively by the cost of the measure and positively by the increased SoS, it is difficult to ground intervention solely on the improvement of the consumers' well being without proper valuation. Banking on the fact that black-outs are extremely rare in real-life, chapter 4 empirically investigates the net cost of CRMs (limited to CP and CM in this analysis). As discussed in section 2.2, CP and CM change the structure of plants' revenues by providing a less volatile component –the capacity revenue. This either directly or indirectly lowers not only the spot prices in the electricity market [de Vries, 2004], but also the market risk (see chapter 2). For a constant level of SoS, CRMs will only be improving the consumer surplus if the sum of those two opposite effects is negative.

Where most studies have been investigating the different costs and benefits of CRMs on a stand alone basis, chapter 4 explores the potential net effect directly by considering the evolution of end-user prices. A regression in differences is performed on a panel of 25 states/countries from both Europe and the US, over 24 years. The econometric methodology accounts for temporal and spatial fixed effects as well as time varying elements such as the gas price and the generation mix. Where CRMs were expected to increase the end-user prices due to transaction costs –regulation-making remains costly *per se*–, coefficients are actually close to zero with large standard deviations. Only restraining the panel to US states provides negative and significant coefficients. In this sense, the cost of precaution might be limited for end consumers, especially if CRMs do effectively improve SoS –as suggested in chapter 2. Extrapolating a bit on the reasons for non significance, heterogeneity appears, once again, as a possible culprit. Indeed, the econometric model is designed to account for the most apparent heterogeneity between the systems but does not account for heterogeneity in CRM design itself. As suggested in chapter 1, design features might play a great role in CRM efficiency in real-world implementations.

4 Reading guide

This introductory chapter sets the scene for the whole study. A broad range of literature has already identified the critical market imperfections that could distort investment incentives and lead to a non-optimal equilibrium. In the absence of precise quantification of the inefficiencies generated –if distortion there is–, the argument on the need for intervention is unsettled. In this context, the identification of the "best" tool to correct such suspected market imperfections is a complicated task. Taking the problem from the other end, CRMs performance assessment banks on the precautionary implementation of CRMs in the past decades and the subsequent literature. With this respect, the approach taken in this study is to consider both regulations and market imperfections as given. This allows to focus on the regulatory choices made and their –potential– consequences. This study thus relates to two main research questions: (i) two chapters investigate the regulation-making process and the details of implementation and (ii) two additional chapters discuss the costs and benefits of CRM implementation under market imperfections.

The first chapter considers the supra-national learning process that has occurred in the last three decades. Through a set of case studies, it highlights the lessons learned from previous regulations in the quest for the perfect regulation. The second chapter reviews the respective performance of the two designs. Reviewing the modeling literature that considers both EOM and CRM(s), it is possible to assess the relative performance of the two under the specific assumptions and eventual market imperfections that are included by the authors. The third chapter looks at the role of uncertainty in design making. Indeed, tailoring a CRM involves a set of stakeholders that are invited to express their views. Considering the particular design feature of requirements definition -*ex ante* versus *ex post*-, the theoretical model highlights actors' preferences for one or the other design when the demand-side acts strategically. Ultimately, the last chapter takes a more holistic view of the problem by seeking a correlation between capacity remuneration implementation and change in end-user prices. Indeed, CRM implementation comes with two opposite effects: the additional price component -increase in end-user prices- should be, at least partially, compensated by the reduction of average wholesale prices -decrease in end-user prices-. This effect is not found robustly different from zero, with a weak tendency to be negative. This concluding chapter suggests that, under the hypothesis that CRMs do not worsen SoS, such a measure might not end up costly for end consumers. The last chapter concludes the dissertation.

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Chapter 1

Real World Capacity Mechanisms: Context, Dynamics and Performance

Abstract

Capacity Remuneration Mechanisms (CRMs) have long been implemented all over the world in order to ensure the SoS. A quick look at contemporaneous designs reveals the diversity of tools available to regulators to meet one common goal. This observation comes in direct opposition with the extended literature that points out how dominant some specific features are compared to others [Mastropietro et al., 2016; Pérez-Arriaga, 2013; Pfeifenberger et al., 2009]. The abundance of such papers reflects the cross-system learning process that has occurred over the past decades, enabling the emergence of such "dominant features". In this framework where designs should converge towards the identified features [Golub et al., 2010], the high variance in designs is puzzling. Convinced that the international context is at least as relevant as the national one to understand the evolution of CRM design [Bennett, 1991; Correljé and de Vries, 2008], we hypothesize that learning does occur, but identification of efficient design features is hindered both by local specifics and technological shocks.

Using a combination of both capacity market rules publications and academic literature, we identify a set of roughly thirty features that can differentiate the CRMs. This provides a framework of comparative analysis applied to 10 systems' regulations that are studied in detail: PJM, ISO-NE, MISO, NYISO, the UK, France, Spain, Ireland, Italy, and Colombia. Their successive implementations and re-designs lead to almost 20 different designs, giving insights on both their spatial and geographical differentiation. The CRM regulatory process does display signs of (social) learning where the most efficient features are increasingly adopted. However, the existence of local specifics prevents designs from fully converging. In a dynamic framework, the convergence process might also be slowed down by exogenous shocks: new technologies create challenges in terms of reliability assessment and performance incentives. The existing designs do not seem to provide the appropriate answer.

1.1 Introduction

All regulatory processes are dynamic and subject to varying forces. CRMs are no exception. To understand the social and economic reach of CRMs, a discussion on the nature of electricity as a good is unavoidable. Indeed, electricity is non-economically storable on a large scale with a rather inelastic demand. In addition, technical constraints cause the system to collapse in case of persistent imbalance. Under those characteristics, available capacity can become binding in periods of high demand, leading to arbitrary rationing as the only way to maintain system stability. Once those elements stated, the importance of security of supply (SoS)¹ is striking, so is its dependence on available capacity. This is where disagreement between economists begins. Indeed, standard economic theory considers capacity to be a byproduct from the energy market: the investments resulting from market outcomes should always be optimal. This conclusion can be questioned in a context of technically inelastic demand, asymmetric investment incentives, imperfect information, risk aversion, and political considerations [Joskow, 2007; Cramton and Stoft, 2005]. If market outcomes were to provoke important blackouts, the social cost of such rationing would be higher than the cost of additional capacity [Keppler, 2017]. Since demand is inelastic, the optimal level of reliability can hardly be estimated, leading to a never-ending discussion on the ability of the energy-only market (EOM)² to provide adequate levels of SoS.

In case capacity adequacy is considered as endangered, public authorities often consider the implementation of CRMs. The concept as we know it nowadays has emerged with power market liberalization, although capacity contracts have been at use for long before that³. In simple terms, CRMs aim at ensuring SoS through capacity contracting to ensure demand can be supplied at any point in time. This is equivalent to explicitly pricing the SoS service provided by available units as an insurance product. In terms of implementation, things become more complicated: How to define capacity adequacy? What is the best way to maintain an adequate reserve margin? What characteristics should be considered as contributing to SoS? How could SoS be financed given the public good attributes of SoS and the heterogeneous preferences of consumers? Those considerations frame CRM implementation choices. As they go along, the designs keep on evolving to match the objectives and gain in efficiency. This chapter highlights the dynamic process driving the regulatory choices.

Scholars often consider that the market imperfections putting SoS at risk are specific to a given system. It results in a broad stream of literature that investigates how well a given design fits a given system. For instance, Newbery [1998] proposes "a critical assessment of the *Pool Review*" where the regulator draws lessons from liberalization and proposes solutions. Kim and Kim [2012] develop the idea of locational capacity payments in Korea to

¹SoS and capacity adequacy are used indifferently, although SoS is formally a broader concept.

²EOMs are useful textbook examples where only the energy produced gets paid for and installed capacity is resulting from this energy market [Stoft, 2002].

³As in the former PJM.

solve the bottlenecks problems and the inefficiency of contemporaneous payments. Devine and Lynch [2017] discuss an alternative design for Ireland, including binding self-declared deratings for each unit in order to induce truth-telling from the firms. On the contrary, a branch of literature takes a more prescriptive approach in an attempt to set out the most efficient design or "must-have" features. Olsina et al. [2014] propose to accurately estimate the scarcity rent before redistributing the capacity payments accordingly (although implicitly this solution is more appropriate for, and tested numerically on, a hydrothermal system). Mastropietro et al. [2016] insists on the importance of the non-compliance penalty. Both Cramton and Stoft and Rodilla, Battle and Perez-Arriaga argue that reliability options might fill the shortcomings of contemporaneous designs [Cramton and Stoft, 2005; Pérez-Arriaga, 2013]. In an attempt to bridge the two streams of literature, Hancher et al. [2015] separately discuss policy, economic and legal challenges in CRM design in the EU (chapters 1 to 11) and existing designs (chapters 12 to 22). Battle and Rodilla [2010] look back on past designs to identify "a set of principles and criteria that should be considered by the regulator when designing a security of supply mechanism". According to them, the elements to be closely monitored by the regulator are the counterparties (buyers and sellers), the reliability product (general recommendations), the contract (lag period and contract duration), price versus quantity and locational prices. This chapter adds to this literature through the identification of system specifics that makes each CRM a unique challenge. It also sets out the learning process that allows the remainder of design features to converge anyways. Focusing on the learning process rather than solely on regulatory recommendation gives a view on the pros and cons of each option, even when they have failed empirically.

With a case study approach, I find that the heterogeneity of electric systems worldwide partially explains the differences in CRM designs because each of them answers a specific SoS problem delineated by the local context (exogenous factors, see section 1.2.1) and the motives for implementation (market imperfections, see section 1.2.2). This system-based approach virtually leads to an infinity of possible tools (features) to design the CRM. Section 1.2.3, discusses the possible options with respect to some thirty design features referring to (i) the high level design, (ii) the product, (iii) the contract (supply-side), (iv) the demand for capacity, (v) the market and (vi) the contribution from non-conventional capacity. However, the bottom-up approach where the local specifics drive the design veils the role of common technological shocks and informational influences occurring at the supra-national level. Adding to the literature with this respect, the framework developed accounts not only for the local forces influencing the design of a CRM, but also considers the global environment in which the regulation is designed. Indeed, knowledge, as much as new technologies flow across borders, creating a common environment for all the contemporary designs. While new technologies act as an exogenous shock, knowledge diffusion tends to homogenize the decision making. Learning is the key to understand the interactions between the global and the local environments (see section 1.2.4 and section 1.2.5). Public authorities do not only learn from their own

experiences, but also others, creating structural interdependences between all the designs in place. Over time, a form a convergence in design emerges.

The framework developed in section 1.2 is supported by empirical evidence. Indeed, the analysis of design choices in ten systems since the 90s reveals the difficulty of abstracting from the global context to fully understand design choices. Three learning cycles are identified which leads section 1.3 to present the different designs in chronological order rather than on a system basis. In the absence of previous experience, only the local context will influence the design: exogenous factors, motives, stakeholders' view, etc. This happens to characterize the CRMs implemented in the 90s (see section 1.3.1). The systems' heterogeneity and the absence of previous experience justify the dissimilarities. However, after a few years, feedback from the design implemented in various systems emerges, giving additional information on the relative efficiency of design features and shaping, year after year, the toolbox at hand. The designs implemented in the 2000s, seem to present signs of convergence, indicating that empirical feedback has identified "dominant" and "dominated" features, reducing the range of possibly efficient designs (see section 1.3.2). This phenomenon becomes more noticeable in the 2010s (see section 1.3.3): basically, all CRM implementations present apparent similarities that can be considered as converging features. Nonetheless, the devil is in the details: the integration of new technologies initiated in the previous period does not seem to have found practical regulatory answers. With this respect, the range of possible designs is then broadening until satisfactory means of integration are found –which is likely to occur during the decade to come. By identifying the increasing similarities between the implemented CRM designs in 10 systems, I am able to set out the features increasingly adopted. Under the sound hypothesis that rational public authorities aim for efficient design, those features are considered as "dominant". The pace of adoption of those "dominant" features informs on the length of learning cycles in the specific case of CRM regulation.

As briefly exposed, this paper develops a framework to analyze the evolution of CRMs not only from a given electric system perspective but also considering the international context. Indeed, the local peculiarities tend to be vectors of divergence, so are the technological shocks continuously faced by the industry. On the contrary, reasoning in terms of transnational learning opens a new understanding of the convergence being observed in CRM designs. Evidence of learning is indeed found, and the increasingly similar beliefs in terms of good practices for CRM design reduce their diversity.

1.2 Dynamics of CRM design

Although in opposition to the prescriptive nature of neoclassical theory, case studies represent a useful branch of the economic literature, highlighting that various standard hypotheses are not verified empirically. For instance, agents are not homogeneous, neither is the market perfectly competitive or information flowing unhindered. In this sense, the literature often agrees there may not be one design to suit all systems [Batlle and Rodilla,

2010], yet, some observers also argue for the implementation of given features considered as "must-have" for a well functioning CRM [Batlle and Rodilla, 2010; Pfeifenberger et al., 2009]. Joining the two approaches, this section develops a conceptual framework where the reach of the lessons from international experience is limited both by local peculiarities and technological change [Bennett, 1991; Correljé and de Vries, 2008]. With this in mind, it is useful to think of all the features that can compose a CRM, as a toolbox for the regulator. This toolbox is affected by various forces that limit the number of tools considered *in fine*. Given the local context and motives for implementation, some tools are more relevant than others. In turn, considering the contemporaneous stock of knowledge (lessons from international experience), some tools can be supposed more efficient than others. Accounting for those two sources of information –local and international– and adjusting for policy objectives and stakeholders' view, a sound CRM, fitted to the considered system emerges.

1.2.1 Answering local needs

Exogenous factors, specific to each system, partly determine the nature of the institutions [Correljé and de Vries, 2008]. For instance, system geography plays a vital role with respect to the capacity needs because it influences the demography of a region, its economic development, and openness. Geography also determines the natural endowments that, in turn, affect the relative competitiveness of technologies.

It thus drives the electricity mix: local fuel(s) naturally emerge as a dominant means of electricity production. Similarly, renewable power production faces location-specific constraints. Most renewables only thrive in given environments: hydropower plants require specific landscape, geothermal plants usually exist around volcanoes while wind turbines are settled on flatlands and solar panels in sunny areas. In addition to geography, they are often weather dependent: a common misconception is that hydro-dominated power systems do not face important SoS threats thanks to their storage capabilities - Norway is often taken as an example with this respect. However, Latin American countries such as Colombia do benefit from huge hydro-power capacities, but face significant variations in inflows from year to year due to natural phenomena⁴ and implemented reliability schemes. This extreme example remains valid for any mean of production: the location of production units influences their efficiency, reliability, and costs.

The partial exogeneity of supply units' location would not be constraining if the demand pool location was not exogeneous as well, creating system constraints. Unfortunately, the dynamics of supply and demand are unsynchronous: while the end of the coal era has decreased local demand in industrial basins in Europe, close-by units remain operating, and their output has to be carried further away and network costs vary according to local conditions. Consequently, the choices in terms of CRM design shall differ in the presence of bottlenecks: local capacity needs will be considered instead of the aggregated peak. As

⁴El niño southern oscillation lasts two to seven years, alternating of dry and wet periods.

stated above, SoS dramatically depends on the ability of the system to supply the entire demand. The underlying requirement is accurate demand forecasting. However, the size of the market usually plays a significant role in load predictability, and consequently, in concerns on SoS. Similarly, systems connectedness allows to average out some of the risks of extreme events, but it might also require some sort of regulatory compatibility with the institutions in the neighboring systems. In this sense, the exogenous factors that define the least-cost power system will also define both the SoS risk and the design of the CRM considered as a potential solution.

When considering capacity adequacy, the characteristics of the economy also matter: they affect the investors' expectations and the opportunity cost of investing in a different sector or country. A high expected economic growth foretells an increasing electricity demand. This would augur a need for investments, but also boost investors' expectations. Similarly, financing is often facilitated in countries with high growth expectations. On the contrary, developed countries currently face low economic growth, which, combined with an ongoing energy transition, leads both to electricity demand stagnation and reduced investment attractiveness. When implementing a CRM, systems with different economic characteristics are likely to invoke distinct motives for implementation, in turn leading to separate designs.

Ultimately, culture and ideology define the institutional context in which a given regulation is to be implemented [North, 1994]. For instance, ideology drives the electricity market design as well as the underlying market imperfection. This affects the decision to implement a CRM and the corresponding design choice. Combined with a recognized level of institutional stability, they partly determine the attractiveness of the market and the confidence of investors in the regulation, which is precisely what CRMs are trying to affect. Last but not least, the influence of stakeholders is likely to affect the design as well since the implementation features of CRMs have significant redistribution effects. Here again, the degree of stakeholder participation is exogenous for being determined by the local culture.

All in all, numerous elements are out of reach of CRM regulation, which thus needs to be tailored to these exogenous conditions. Mainly, they derive from local constraints such as the region geography, economy as well as culture, and ideology. For instance, the Nordic systems have been precursors in terms of market integration (first international power exchange) and benefit from cheap resources (hydropower, nuclear, Norwegian gas) as well as export capabilities that tend to reassure investors. The position of those countries has historically been against CRMs. However, even strong similarities generate different risk factors since Finland and Sweden have both implemented -temporary- strategic reserve (although still against CRMs) suggesting that exogenous factors do not solely determine the implementation decision: motives have a role to play.

1.2.2 Motives for CRM implementation

Exogenous factors drive the potential need for CRM. However, the analysis of such a need, that drives -or not- CRM implementation results from the preference for SoS. In turn, the market imperfections put forward as a motive for implementation will shape the design.

In the case of electricity markets, a useful tool to understand the choices in terms of design is the "energy trilemma". The "energy trilemma" states the inability of a system to meet criteria of affordability, sustainability, and SoS at the same time. Although often applied to the energy sector as a whole, this concept is also translated for electricity markets: it was explicitly used by the Department of Climate Change (DECC) in the UK when reforming the power market in 2013.

Liberalization, in the hope of better cost optimization, belongs to the affordability part. However, besides cost reduction, risks on the SoS were also identified. Strong actions to mitigate climate change belong to the objective of sustainability. In 2005, the EU Emissions Trading System (EU ETS) was launched to curb CO₂ emissions in the European Union while the 20-20-20 package decided in 2007 for a 20% reduction in CO₂ emissions⁵, along with 20% of the energy produced from renewable sources and a 20% improvement in energy efficiency. In parallel, a significant number of countries, led by Germany, started to subsidize renewable technologies such as solar panels, wind turbines or wave and tidal energy, leading to steeper learning curves and enabling the non-conventional technologies to become competitive. CRM implementation emanates from a concern regarding the third target: the security of supply. It seeks to secure the amount of capacity considered as necessary to avoid blackouts. Indeed, SoS is a costly objective as it requires investments in plants that mostly have an insurance value: they are expected to produce very rarely, during extreme rare events. The SoS objective also often goes against the sustainability objective since conventional (dispatchable) are *de facto* providing more SoS by nameplate capacity for being more reliable than renewable technologies⁶. Considering that each system aims for a specific combination of the three objectives of the trilemma, the market will be designed accordingly.

In addition, CRMs are implemented as insurance against insufficient capacity investment in the electricity market. Distrust toward energy only markets (EOMs) is common to all systems implementing a CRM. However, the reasons for such a lack of faith vary strongly: several market imperfections have been identified in the literature, and the chosen design strongly depends on the targeted imperfections.

With respect to capacity adequacy, Cramton and Ockenfels [2012] consider that demand inelasticity makes efficient market outcomes in terms of SoS unlikely, they also judge the electricity market too risky to attract sufficient investments. Indeed, the high price volatility of EOMs pushes both the financing costs and the expected rate of return up.

⁵Compared to 1990 levels.

⁶This is given thermal generators do invest in the maintenance and fuel supply as discussed in the following sections.

Joskow [2007] shows empirical evidence of missing money in organized wholesale markets in the US and Joskow [2008] explains its existence by the inefficient pricing on wholesale spot markets for energy and operating reserves. In a broader view, Cramton and Stoft [2006] show that markets with adequate installed capacity are characterized by missing money: "From the investor's point of view, when capacity is adequate, peakers can expect to cover only one-quarter of their fixed costs. No one with such expectations will invest." In turn, Keppler [2017] argues that the lumpiness of investments in the power sector, combined with the asymmetric incentives, lead to structural underinvestment in power markets. All those justifications might hold in a given system, but extreme events remain too rare to statistically investigate the actual SoS level and the role of such market imperfections in blackout realization.

Given the lack of academic consensus on the actual need for capacity remuneration, but also on the roots of inadequacy, the implementation of a CRM results in a highly political decision. For instance, while the EU advises first to improve energy markets, France and the UK have decided to implement a CRM anyway. Considering that the social cost of under procurement (blackouts) is higher than the social cost of over procurement, regulators argue that the EOM cannot be trusted with the SoS. The reason for distrust is, however, meaningful with respect to the design of the CRM. Built as a complement to the energy market that would incentivize availability and investments, CRM designs are usually in line with the identified market imperfections to efficiently correct them. In addition, renewable energies' integration has shifted the SoS problem from a rather "simple" question of scarcity pricing to a more complex topic. Indeed, depending on the correlation between renewable production and demand⁷, any unit of the merit order (being base, mid-merit or peak) might struggle to recover their costs [Green and Léautier, 2015], they have different risk factors. While peakers' risk factor dramatically lies on scarcity pricing, base plants rather count on capacity factors (quantities): punctual high prices would not affect much their average revenues. This being said, it seems obvious that price and quantity risks will require different mitigation mechanisms. According to Parsons and De Sisternes [2016], "policy makers with different visions for the pace of additional renewable capacity are going to have different views about the risks to capacity adequacy".

1.2.3 Differentiating features of CRMs: a rich toolbox

Exogenous factors and motives make the regulatory problem specific to each system. This results in different designs coexisting around the world and numerous examples of how design features can be selected and assembled to create a CRM. Batlle and Rodilla [2010] already identified a set of design elements the regulator should consider, namely they advise for careful devising of the counterparties (buyers and sellers), the reliability product (general recommendations), the contract (lag period and contract duration), price versus

⁷See Léautier [2019] chapter 8 for an analysis of the policy issues of RES integration and their impact on the generation mix.

quantity and locational prices. In a more descriptive approach we define roughly thirty features that can be used to accurately describe any CRM and gather them into 6 main categories: Choice of high level design (table 1.1), Product (table 1.2), Contract - supply-side (table 1.3), Demand for capacity (table 1.4), Market (table 1.5), and Contribution from non-conventional technologies (table 1.6). Given the diversity and complexity of CRMs around the world, this does not seek exhaustiveness, but provides a useful overview of the main issues at stake. More specifically, it allows to understand the ins and outs and compare each design.

High level design

The high-level design refers to the type of CRM with the actors involved, its degree of market orientation, the degree of centralization as well as whether it is volume or price-driven. These are the first design decisions to be taken. In addition, they define the subset of features that will be relevant in this specific design. If the market-related features will only be needed in competitive environments, this is also true for market power mitigation. The extent to which transparency is required also differs depending on the type of procurement. In turn, the degree of centralization will partially determine the degree of demand-side (LSEs) involvement in the mechanisms as well as the incentives for peak demand reduction. Indeed, in centralized mechanisms, the role of the demand-side tends to be limited, but decentralized ones require a careful definition of the demand-side obligations.

Those standard categories are, however, less straightforward than one could think. For instance, more or less precise target price and quantities are required for both volume and price-based CRMs. Otherwise, there is a risk to over or under remunerate capacity compared to the reliability objective. Volume-based CRMs are often organized as markets in order to be as truth revealing as possible and limit the cost of the measure. However, given the structural market power, competitive behavior and truth-telling are unlikely: price targets are used to identify and mitigate market power, rendering the dichotomy price versus quantity obsolete (see discussion in section 1.2.3 on the demand curve and market power mitigation). This remains valid for decentralized CRMs where obligations are still partially centrally defined. A volume without price definition generates volatility and hinders the identification of market power. On the contrary, defining a price without an idea of the need for capacity is unlikely to give the right incentives.

The participation constraints (eligible capacity and level of centralization) shapes the overall design. A mechanism targeted towards investment will result less costly but eventually distortive in the short run⁸. The decision to include non-conventional technologies in the CRM complicates the design but it also grants those actors a fair remuneration that might be beneficial to the system as a whole. Similarly, decentralization is expected to empower the demand-side, leading to additional DR participation. In turn, those actors

⁸In the long run, all units are replaced and benefit from the same framework [Hach et al., 2016].

identify as stakeholders and will be able to influence the design.

All in all, high-level design features (see table 1.1) define the complexity of the CRM by limiting the number of actors and their playing field. As such, they drive the remaining features of the mechanism⁹. This explains why most proposed taxonomies focus on those elements.

| Specific feature | Description |
|----------------------------|---|
| Type of CRM implemented | The CRMs can be more or less market-oriented. Fully regulated capacity or price mechanisms are less and less implemented, and markets allow for an easier combination of the two. |
| Volume-based/ Price-based | Volume-based tend to administratively set the volume, while price-based focus on prices. The latest CRMs implemented are all volume-based under the consideration that this is the efficient way to secure an amount of capacity regarded as optimal without over or under remunerating units. However, strategic reserves are still considered for short-term adequacy problems as in Germany or Belgium (2015). |
| Centralized/ Decentralized | CRMs are mainly centralized with the system operator procuring the capacity required for the whole system. France has recently implemented a decentralized CRM (LSEs directly cover their capacity requirements) that remain to prove its effectiveness. Otherwise, former decentralized mechanisms (MISO, PJM) have transitioned towards additional central characteristics. |
| Actors | The system operator is often a key actor for defining the targeted level of capacity to be procured. On the supply-side, generation companies see their performance monitored in exchange for capacity remuneration. Decentralized mechanisms also directly involve retailers as in MISO and France. |

Table 1.1: High level design features

Product

Product definition always reflects the policy objectives. It is key in ensuring the efficacy of the measure, but also the affordability and even sustainability. The following equation reflects the constraints any CRM is subject to in order to ensure the SoS¹⁰:

$$\sum (\underbrace{capacity_i}_{\text{Eligible unit}} * \underbrace{derating_i}_{\text{Contribution}}) = Peak * (1 + \underbrace{\text{scaling factor}}_{\text{Non eligible capacity's contribution \& reserve margin}}) \quad (1.1)$$

⁹For instance, British stakeholders complained in their answer to the 2011 consultation [DECC, 2011] that discussing implementation details without a view on high-level features was a complex exercise.

¹⁰The right hand side of the equation will be further discussed in section 1.2.3.

To maintain equality, the regulator can play with any of those parameters. Most commonly, the eligible capacity is different from one system to another, and this only needs to be compensated by the scaling factor. Indeed, a smaller basis for eligible capacity cuts costs. A targeted design is then easier and cheaper to implement, but it is also considered as more distortive and unfair to existing capacity. Another example of the importance of the scaling factor is the accounting for foreign contribution to SoS: the implicit contribution of interconnection is fully covered through a reduction in this parameter. Similarly, capacity is sometimes procured out of the CRM (as nuclear and renewables in the UK) and non-eligible technologies regularly claim their contribution to SoS (and the right to benefit from capacity remuneration). As a matter of fact, they are always considered implicitly in the equation.

| Specific feature | Description |
|----------------------|--|
| Eligible capacity | The principle of non discrimination between technologies has been firmly stated by economists from the beginning: each unit deserves capacity remuneration in proportion to its contribution to the SoS. This is to say irrespective of their age, carbon intensity or any other technical characteristics that does not affect their reliability. This recommendation is not always followed and some CRMs might be targeted towards new capacities to favor investment, or towards old units to prevent retirement. Others might exclude non-conventional technologies from participating, under the argument that they are no reliable (although they contribute to SoS). |
| Methods for derating | When allowing all capacity units to receive a capacity remuneration, the regulation needs to account for the huge differences in reliability from one unit to the other. This is to both ensure SoS and standardize the capacity product. Although it is broadly used, the method varies from one system to another. Historical performance is often considered as a proxy for the delivery year performance of a given unit. Technology-wide deratings, averaging out the performances of the units within a group of similar units, diluting the incentive. In turn, <i>ex post</i> assessment restores the incentives to perform but creates additional risk. |
| Tradable quantities | The deratings make all "firm capacity" or "reliable capacity" homogeneous, allowing for the creation of a market and the secondary trade of capacity certificates. Having tradable quantities require the possibility of passing the contracted obligation from one party to the other: this means that capacity is often considered as a financial product with physical back up. |

Table 1.2: Product definition's features

The derating factors aim at measuring the actual contribution of units to SoS. As such,

they are used to ensure fair remuneration to every unit based on the best estimates of its performance. However, the methods for derating still vary: some use each unit's historical performance, which incentivizes availability since it conditions the futures capacity revenues. However, such metrics are subject to a variability and potential arbitrage strategies that do not serve the purpose of accurate estimation of capacity needs. Technology-specific deratings are a proxy that averages out units' availability variability, as such, it requires additional care in controlling each unit's compliance with its obligations. Actual performance can also be used, but it creates additional uncertainty on generators' revenues for including *ex post* components. Considering that CRMs often explicitly seek to reduce the market risk for investors, this might be counterproductive. When carefully defined, derated capacities lead to homogeneous "firm capacity" considered tradeable if needed (especially with forward CRMs - see section 1.2.3).

In summary, the capacity product results from the supply-side of eq. (1.1) (left-hand side), making sure that enough capacity is committed to meet the reliability target. If such arithmetic not only defines what capacity is entitled to remuneration but also standardizes the capacity product to allow trading. Then, the basis for a market-based approach is set. Whether the capacity remuneration is administratively or competitively set does not necessarily affect the objective: ensure SoS. To do so, contractual rights and obligations are also features to be clearly defined.

Contract (supply-side)

In exchange for the payment, capacity resources are required to actually contribute to SoS: this is what we call the contract part of the design. There are two types of obligations: those necessary to be eligible such as network connection, fuel supply contract, monitoring possibilities, etc, and those linked to the actual contribution to the SoS. One way to ensure so is to require day-ahead bidding, but units performance can also be valued in terms of availability and/or production: this is assessed during scarcity episodes. This requires the thorough setting of a critical period indicator so each actor can clearly identify scarcity periods. The critical period indicators are as numerous as the CRMs themselves, depending on the scarcity drivers in each system. Some rely on economics indicators (energy price levels), others on technical indicators (brown-out measures, demand response schemes activation) or even on expected scarcity in a short horizon. They sometimes trigger the obligation but can also restrain the activation to specific periods (winter or summer months, peak hours, etc), which ease the maintenance (or charging) planning for the committed units. The diversity of scarcity indicators further blurs the borders between the types of CRMs: ROs used to be the main financial tool, but a CM with a financial scarcity indicator could yield to similar results. In this sense, we will further consider the product as being "capacity", even though this is a simplification.

The delivery period states the duration of the obligation. It ranges from a day to several months during which the unit needs to comply with its contractual obligations. Mainly,

| Specific feature | Description |
|---------------------------|--|
| Obligation (supply) | Obligations can vary but have in common ensuring that contribution at scarcity is possible. It can include proving network connection, contracted fuel supply, but also efficient planning of maintenance or performance during scarcity events or bidding on the day-ahead market. |
| Critical period indicator | The critical period indicators pinpoint scarcity events. As such, they rely on economics indicators (energy price levels), others on technical indicators (brownout measures, demand response schemes activation) or even on expected scarcity in a short horizon. |
| Delivery period | The delivery period ranges from one day to several years. Short delivery periods allow for a better assessment of actors' contribution to the level of scarcity. Longer delivery periods provide more stable investment signals, but also require a more complex (statistical) assessment of the contributions. Special cases are sometimes provided for investments that can benefit from long-term contracts. |
| Non-compliance penalties | Non-compliance penalties are often proportional to the capacity price on a given market. It is the option value of not delivering. |
| Lag period | The lag period is the time between the beginning of the contract (when the capacity is exchanged) and the beginning of the obligations. It ranges from a couple of hours to several years, usually in line with the delivery period: the longer the delivery period, the longer the lag period tends to be (stabilize investors expectations). |
| Contract duration | The contract typically starts when the capacity is sold (bought) and ends when the parties have fulfilled all obligations. Similarly, it can thus vary from a couple of days to several years |
| Exit penalties | Exit penalties are often contingent to CRMs that include a significant lag period. Indeed, the exit penalty is the option value of exiting (resp not entering) before delivery. |
| Market power mitigation | Market power mitigation is often twofold: first identification and then mitigation. Identification is focused on obvious dominant actors or pivotal buyer/provider, and mitigation is contingent on the strategies developed: usually involve a price cap and/or a price floor on their bids to limit the market maker behavior, but quantity related measures can also emerge. Information disclosure (transparency) is another tool to both identify and limit market power. |
| Transparency measures | Transparency measures relate to the precision and amount of publicly disclosed information. They are usually conditioned to the structure of the market, the competition, as well as the type of CRM at hand. |
| Verification means | The verification regards how the obligations of each party are met. It often relies on existing operational controls for the energy market, but might also rely on actors declaration. |

Table 1.3: Contract related features: supply-side

the shorter the duration, the more accurate the price signal (based on scarcity) can be - to the expense of price stability. On the contrary, more extended delivery periods provide better investment incentives. A short delivery period then reduces the need for obligation specification and the contingent verification and penalty because the uncertainty on plants' availability is reasonably low. Some designs also grant investments with long-term contracts where plants receive the clearing price for several years in exchange for delivering the reliability product over the period. The duration of such contracts can significantly vary, up to several decades. This latter case is mainly used where investments in hydropower are considered. Indeed, long-term contracts partially isolate revenues from the market risk, and this becomes more and more valuable as the investment cost gets greater, leading to longer contracts. Two approaches are often opposed with this respect: on the one hand, "technology-neutral" can be understood as not favoring one technology over the other. In this sense, the long-term contract duration might be indexed on the capital intensity of the investment. On the other hand, "technology-neutral" also has an egalitarian meaning that requires all technologies to benefit from the same conditions, independently of their characteristics. When this meaning is favored, the pre-defined duration of the contract will tend to favor one technology compared to the other: the longer, the more suited to capital intensive investments, but also the more rent it might create for "cheaper" technologies.

Carefully designed verification means and non-compliance penalties are needed to enforce the obligation. Verification means present a great variety of complexity. As a matter of fact, checking an obligation to bid on the day-ahead is fairly straight-forward. However, an obligation to produce often requires the involvement of third parties such as TSOs and DSOs to recover the information. Alternatively, self-assessment is sometimes considered sufficient. Non-compliance penalties are the natural corollary of such obligations: they represent the option value of committing the capacity and are thus frequently indexed on the capacity price. They are little necessary for the most short-term mechanisms. Too low penalties lead to inefficient outcomes¹¹. Conversely, too high penalties render the contract too risky: a cap on penalties is often added to limit the generators' liability. In the presence of a lag period between capacity procurement and the beginning of the obligation, exit penalties might be useful as well.

Indeed, the lag period can range from day-ahead to several years ahead. The implications are mainly twofold. First, the longer the lag period, the higher the uncertainty around both the actual need for capacity and its ability to be available during the delivery period. Then, the price signal might not reflect the actual scarcity conditions at delivery. Second, as the time required to build a new plant is at least three years (for gas turbines), there is a dichotomy between very short lag periods (say lower than a month) and over three years ones which allows new projects to participate. Any lag period in between the two

¹¹The UK recently experienced the bailout of the only new built that cleared the 2014 auction (Trafford power plant), meaning that the penalty was not high enough to deter taking an option <https://uk.reuters.com/article/uk-britain-trafford-gas-plant-idUKKBN1491E2> accessed on March 30th, 2019.

presents limited interest. Consequently, short lag periods *de facto* reduce the investment impulse and improve the performance incentive compared to a longer one. With respect to the latter, it is worth noting that different technologies require different construction times. A three-year lead-time would foster the entry of peakers but might not allow other technologies to enter the market as they require additional construction time.

In addition, market power usually requires special attention in electricity markets, mitigation methods, as well as transparency measures, are carefully devised. Market power mitigation depends on the structure of competition on the market and the possible expression of market power. It is often twofold: identification of market power and then mitigation. Once the actors who are in a position to exercise market power are identified (usually either obvious dominant actors or pivotal buyer/provider): the relevant mitigation processes are implemented. It usually involves a price cap and/or a price floor on their bids to limit the market maker behavior, but quantity related measures can also emerge. With respect to transparency measures, it is commonly admitted that it should be included. They often relate to the preciseness of the published information regarding prices, quantities, and actors involved¹². Mainly, in the absence of competitive allocation, the selection criteria should be transparent –which is not always the case. Otherwise, they are usually conditioned to the structure of the market and the competition. They also depend on the type of CRM at hand. Typically, auction results are published without bid information, the aggregated supply curve is available, but the underlying data (anonymous) are not always accessible.

Once the general terms of remuneration are clarified, the contract seeks to make sure the contracted capacity will serve its purpose. It thus defines obligations and penalties as well as the usual contract timing. Again, these considerations are mostly independent of the form of procurement. They also leave aside the question of demand formation, which is explained in the next section.

Demand for capacity

The increasing hybridization of CRMs compared to the usual taxonomy leads to common concerns in terms of features, both on the supply and demand-side. This phenomenon has led to more and more market-based CRMs being implemented, justifying the following discussion.

As discussed earlier, the demand-side features result mainly from the high-level ones. Decentralized CRMs require full integration of LSEs with a definition of their duties and rights. As for centralized mechanisms, the experience has shown the importance of demand curve specification on prices and market power. Although the objective is always to cover the peak demand increased by reserve margin, the capacity target depends on the design of the CRM. This is to say, the demand target is mainly contingent on the

¹²Lazarczyk and Coq [2018] highlight a temporal trade-off regarding information disclosure in electricity markets: data is either disclosed quickly but aggregated or in a more detailed version sometime after realization.

| Specific feature | Description |
|----------------------|--|
| Demand target | The capacity objective (demand) is always centrally defined as $\text{Peak}(1+\text{scaling factor})$. The level of the reserve margin depends on the specifics of each system. The target can either be binding when the total capacity to procure is set <i>ex ante</i> (LSEs have no choice but to pay for their share, irrespective of the realized aggregated demand during the delivery year), or indicative (price-based or volume-based with <i>ex post</i> requirements indexed on the realizations of demand levels in the delivery year). |
| Missing money & CONE | The definition of a "price target" is necessary to characterize the level of payments (price-based) and eventually, the demand elasticity (central procurement). Also, economic assessment of price caps and price floors are useful for market power mitigation: the net Cost Of New Entry (CONE) is computed and serves as a benchmark for all price-related parameters. Conceptually, it is the missing money of a new entrant, the amount it would bid on the capacity market. The parameters for net CONE calculation can vary, but the concept is central and used in almost all demand parametrization. |
| Demand curve | The demand target can be more or less firm, depending on the slope of the demand (the elasticity of demand with respect to the SoS). The actual target can also depend on peak demand realization, in which case, the elasticity of demand reflects the opportunity cost of under or over procurement under uncertainty. |
| Obligation (Demand) | On the demand-side, there is an obligation to pay for the SoS. With centralized procurement, be it capacity payment or market-based, the capacity charge is dealt on load-serving entities (LSEs) often based on their (portfolio) share of peak demand. With decentralized procurement cost allocation can be more accurate (<i>ex post</i> requirements), which also results riskier for LSEs. |

Table 1.4: Demand features

supply-side characteristics described in section 1.2.3. The peak demand is scaled up or down in order to account for the non-eligible capacity and the reserve margin (eq. (1.1)). This approach is used in both volume-based and price-based CRMs. While the role of the demand target is obvious in quantity-based CRMs, it is less so for their counterpart: regulators use the capacity target as a benchmark to set the price. Indeed, the level of remuneration to avoid exit is different from the level fostering entry and knowing system needs reduces the risk of creating excessive rents. This section will thus make little difference between the modes of procurement.

However, a firm quantity target relates to a market-based CRM with an inelastic demand

(be it in a centralized CRM or not). Economically, inelastic demands are characterized by high price volatility, as it is already the case on the electricity markets. Two elements pledge for a more elastic demand: the existence of a certain level of load shedding available at peak, and the aim of CRMs that is often to reduce the market risk for investors -which requires low capacity price volatility.

Sloped demand curves only apply to centralized markets (volume-based)¹³. They move capacity markets away from their conventional categorization as volume-based mechanisms: including a price component in the parametrization of the demand locates the CRM type in between price and volume-based. When this path is taken, the shape of the demand curve becomes an essential element of design: which slope, convexity or boundaries should be considered? Trying to account for market fundamentals, the shape of the demand curve often depends on the targeted price –the expected competitive bid of a new entrant (net CONE)¹⁴– as much as the targeted quantity.

A fine setting of demand parameters is essential to avoid over and under procurement since the end-users are here captive. The regulator acts in their name to ensure the SoS by designing a CRM. They, however, remain those who stand in benefit of the mechanisms. As such, they pay the capacity charge through their retailers. This is true for all CRMs. Indeed, the central buyer often requires that reach retailer contribute to the capacity charge in proportionally to its contribution to the issue (or directly procure capacity). In this latter case, requirement definition (demand-side obligations) shaped the risk born by the LSEs. Indeed, *ex ante* requirements lead to a similar liability compared to a centralized CRM, whereas *ex post* assessment (realized peak demand) shifts the risk on the demand-side. One way to mitigate this is to consider normalized realized peak demand so to partially hedge LSEs against non-controllable uncertainty while preserving load management incentives. For instance, peak load is, at least, weather normalized in most designs.

Market

When capacity remuneration is allocated through a competitive process, a market is created. As often, market implementation aims at efficient pricing. In the presence of bottlenecks, they shall account for congestion and display locational differences. The necessity to account for locational constraints is common to every CRM, else, they might fail their purpose –resulting in out-of-capacity market capacity procurement. In special cases, however, the congestion might not occur at scarcity, and locational energy prices would not always imply locational capacity prices.

In practice, most competitive CRMs implemented centralized auctions, but bilateral contracting often remain an open option for the Load Serving Entities (LSEs) in charge of

¹³Other modes of procurement might have some degree of demand elasticity, but it would be endogenously determined and thus are not a CRM feature.

¹⁴This benchmark is obviously useful in a price-based CRM as well.

| Specific feature | Description |
|-----------------------------------|---|
| Locational | Locational pricing is commonly implemented in systems that already face congestion and have locational energy prices as well. |
| Bilateral and/or auctions | In practice several streams of capacity procurement coexist: bilateral and/or voluntary or compulsory markets. For decentralized markets, the choice depends on the degree of integration of the actors as market power and entry barriers have sometimes emerged from bilateral procurement. |
| <i>Ex ante</i> Adjustment auction | The longer the lag period, the lower the preciseness of the demand forecasts. This is why adjustment auctions can be implemented for the actors to adjust their positions. |
| <i>Ex post</i> Adjustment auction | <i>Ex post</i> adjustment auctions are unnecessary when the capacity target is defined as <i>ex ante</i> and binding. However, when the demand for capacity depends on the delivery year realization, actors might need to adjust their positions <i>ex post</i> . |

Table 1.5: Market features

their own SoS. The two options imply different market organizations. Where bilateral contracting suggests rather continuous trading in time, auctions require a specific timing for the price to be representative. Indeed, the higher the volume traded, the more efficient the auction. In this sense, CRMs limit the number of auctions to account for the trade-off liquidity/volumes: the longer the lag period, the more relevant this consideration is. Decentralized CRMs naturally face similar inter-temporal adjustments.

A lone auction (be it centralized or not) procures the demand target all at once, but in case of underestimation of the target with a long lag period, adjustment auctions are usually allowed by the regulation. The justification for *ex post* adjustment auctions is related: if the level of the demand-side obligation is based on the realized demand instead of the forecasted one (see section 1.2.3), then one's expectation might be proven wrong by empirics and need to adjust its level of capacity procurement (up or down). This is the main difference between being obligated based on the level of realized demand (*ex post* requirement) or the share of the realized demand (*ex ante* requirements). In the first case, capacity certificates still have value after the delivery year because the agents might have been mistaken. In the second case, the forecasted target has been secured once and for all, independently of the realizations. The actual demand will only affect the share of the capacity charge born by each LSE and the actual level of SoS.

As markets define how the price emerges¹⁵ and the margin for market power expression. The forms of trading allowed then have a great impact on the accuracy of the resulting price signal. The special case of non-conventional technologies has been little discussed so

¹⁵Auction rules and clearing processes have been left aside.

far, although their integration creates challenges, which, if not carefully considered might distort the market.

Contribution from non-conventional technologies

Until a few years ago, high-level design mainly, but also product and contract definition as well as demand-side obligations and market organization were the core of the discussion. However, but the increased competitiveness of non-conventional technologies made homogeneous regulation difficult to implement. Indeed, conventional-generation might include a variety of technologies and technical characteristics, but they remain reasonably homogeneous in their way to contribute to the SoS. Non-conventional technologies, however, have a diverse and more complex relationship with reliability: their contribution can rely on statistics as for intermittent renewable, but also be limited in time as for storage or demand response.

In this sense, their inclusion into capacity schemes requires a greater level of complexity on the elements of the supply-side. The obligation needs to be limited in time for demand response and storage to be able to comply. Their deratings cannot solely rely on outages as if the units were able to run the rest of the time without constraints. The verification means shall also be adapted since non-conventional units are often connected to the distribution grid and not the transmission grid.

They also differ from conventional generation in their behavior: renewables have a variable production while DR and storage consume more than they produce. Then, to verify compliance, production assessment is insufficient: the whole consumption/ production pattern has to be scrutinized. Those are costly regulatory adjustments both in terms of resources and technical investment, leading to a slow integration of non-conventional technologies. Consequently, legal eligibility to capacity remuneration is sometimes combined with technical impediment¹⁶.

Renewables such as biofuels, wind, and solar have long been competitive and accounted for in CRMs, but interconnectors' participation requires a form of compatibility of neighboring regulations, which is more demanding in some contexts¹⁷. Similarly to storage, demand response acts as demand elasticity and presents a great potential to make CRMs unneeded someday through their ability to affect peak demand. Precisely because it would solve the root of the problem [Keppler, 2017], they are challenging to value within a CRM. On the contrary, energy efficiency programs only translate the problem for being non-dispatchable: they affect the shape of the load, which has a high value in the short-term. In the long-term, however, the mix adapts to the shape of the load (entry and exit of units). This is why the valuation of energy efficiency contribution to SoS is not straight

¹⁶Capacity products are often characterized by size constraints that force aggregation of DR and/or storage units [Gissey et al., 2018]. Until recently, the obligations did not limit the number of consecutive hours a capacity product had to be available while storage units work on charge/discharge cycles.

¹⁷See section 1.2.5 for additional details.

| Specific feature | Description |
|--------------------|--|
| Deratings | The estimation of non-conventional technologies actual reliability is a true challenge and remains a learning process (esp. for storage). Difficulties frequently emerge when the regulation tries to apply a framework designed for the conventional generation to non-conventional ones. Historical availability at peak is often seen as a good proxy for renewable generation. Interconnectors are sometimes considered as generation units, so historical contribution at peak is used, but foreign generators can alternatively take part in the CRM directly, limiting the value of existing interconnectors <i>per se</i> . With respect to demand response, technical ability to monitor the load shed in real-time is commonly required and the derating factor is adjusted based on historical performance. |
| Verification means | Non-conventional capacity often requires special performance assessment. Demand response and storage verification is based on a (system-specific) counterfactual to estimate the level that has been shed. Actual electricity production is used for renewable energies and interconnectors. |
| Interconnectors | The integration of interconnectors or foreign capacity is still regulatorily complex in Europe but has been implemented for long in the US. However, it requires the neighboring systems to have compatible regulations. When foreign capacity can qualify in the CRM, only new interconnectors have value within the CRM (in most cases). |
| DR participation | The difficulty for DR valuation lies in estimating the actual shedding, but the potential of DR in terms of SoS is much higher than a simple contribution to the SoS. Successful integration of DR would make the demand increasingly elastic, easing the efficiency of energy pricing. |
| Energy efficiency | Energy efficiency is controversial, it does contribute to lowering the peak demand, but in a rather static way. Their contribution is thus assessed, and they are only considered as a capacity product for a limited period of time |
| Storage | Storage can usually participate in the CRM, but the rules are not always adapted for efficient integration (this is improving with EU directives and FERC order 841). Indeed, each storage unit has specific technical characteristics that constraint its reliability: they can only produce so many hours straight before they need to recharge (consume). Obligations are sometimes too restrictive to allow for such behavior. |

Table 1.6: Non-conventional technologies' features

forward. It also has a SoS impact limited in time: if eligible, they often can only apply for capacity remuneration for a limited period. For all these reasons, their integration is challenging, but also requires regulatory innovation.

While being rather complex regulations, CRMs can be accurately described through a limited number of elements (roughly thirty) as in the tables 1.1 to 1.6. This categorization parsimoniously portrays the regulations, making some sense out of their diversity. This also identifies the different features possible within the elements. Altogether, they represent the available toolbox to each regulator. Taken at the country level, some features may be irrelevant in a specific context due to exogenous factors and motives (market imperfections), as discussed in the previous sections. Choosing a given design over all the remaining combinations of features is rather subjective when accounting only for local learning (figure 1.1): previous to implementation, the regulator analyses system needs, it then adjusts the design in line with observed performance and agents' behavior to correct imperfections. If adjustments remain insufficient, a structural change in design is deployed to account for new market dynamics. This storyline makes sense in autarky but undermines the reach of learning. In real life, regulators can also observe the choices and even reflections of their counterparts in an international learning process. The following section explores the role of learning the regulatory decision process.

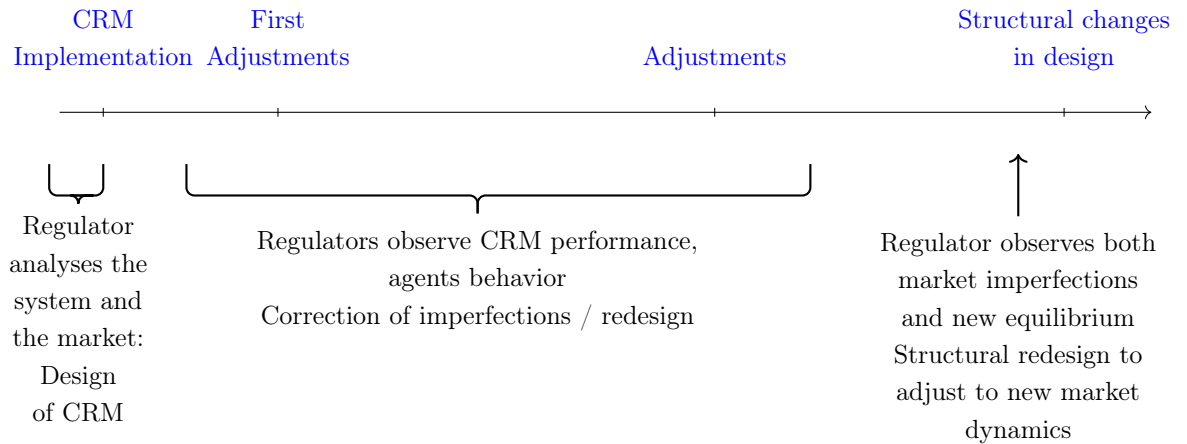


Figure 1.1: Timeline of CRM implementation and redesign at the country level

1.2.4 The international context matters

The bottom-up approach focusing on the system-specific analysis presented in section 1.2.1 and 1.2.2 shall be nuanced. Indeed, decisions are not taken in autarky: information flows through a dense web of regulators and counselors that regularly interact with one another. With this respect, network theory is useful in understanding the effect of information sharing. Social learning models are indeed often used to explain social interactions and information diffusion.

In particular, the repeated linear updating models, also called DeGroot models¹⁸, provide a useful intuition on the learning process that might occur amongst regulators as they seem to fit electricity market interactions. DeGroot (naive) learning refers specifically to the learning process among a set of actors with initial beliefs that they update over time through social interactions (confronting beliefs). In this framework, knowledge and beliefs converge if the network is (i) strongly connected –each regulator is connected to all the others through a finite number of intermediate interactions– and (ii) aperiodic –each regulator averages all the information it receives, including its own, meaning that the same sequence of beliefs cannot happen twice [DeMarzo et al., 2003]. Although DeGroot models do not fully reflect the complexity of regulation-making in a dynamic environment, social learning models have been extensively used in a more qualitative way to analyze policy convergence. In this framework, an individual’s belief is more affected by those of its closest neighbors. This joins North’s theory [North, 1994], where cultural proximity affects regulation.

The literature provides a framework to analyze policy learning that can be applied to the electricity sector regulation. Inkeles [1981] defines policy convergence as "moving from different positions towards the same common point". Illustrating the idea of partial convergence, Bennett [1991] considers five different aspects of the policy that can converge: the goals, the content, the instruments, the outcome, and the style. This paper only focuses on one policy instrument, the CRM. He also categorizes the separate vectors of policy convergence into four categories: convergence through *emulation*, convergence through *elite networking and policy communities*, convergence through *harmonization* and through *penetration*.

The *emulation* is the process of active lesson drawing, where one country is emulating and the other is emulated. It follows that learning alone does not prove *emulation*; it also has to translate in the regulation itself, which consequently makes this form of convergence relevant for policy goals, content, and instruments. It also renders it challenging to exemplify.

The second form of convergence is driven by *elite networking and policy communities*. The rationale here is that similar countries might be involved in regular interactions, which lead to an analogous public debate and the implementation of comparable policies. For instance, the ACER regularly gathers the European regulators, creating a strong stream of exchanges and information flows where they can learn from one another. Another form of transnational group influencing policy-making is academia. For instance, public authorities can resort to well-known scholars such as W. Hogan, P. Joskow, P. Cramp-ton, S. Stoft, D. Newbery, or C. Batlle for the expertise and advice. The consulting firms hired for external validation also end-up being limited world-wide: Brattle Group, Charles River Associates, Frontier economics, FTI Consulting, etc. For instance, Charles River Associates were in charge of the *Capacity Market Gaming and Consistency Assessment*

¹⁸In the continuity of Degroot [1974]’s paper.

for the UK mechanism [Charles River Associates, 2013] as well as *A Case Study in Capacity Market Design and Considerations for Alberta* [Charles River Associates, 2017]. Similarly, the Brattle Group regularly advises US ISOs such as PJM [Pfeifenberger et al., 2009, 2014], MISO [Newell et al., 2010], ERCOT [Newell et al., 2012] and presented *Characteristics of Successful Capacity Markets*¹⁹ at the APEX conference²⁰ 2013, spreading their knowledge not only to system operators and regulators, but also to businesses and academia. Such formal examples of *elite networking and policy communities* are plethora and obviously, do not include informal transmission of information.

The third category of convergence is through *harmonization* where a supranational body can impose forms of regulation. The interdependence is here a key element leading states to recognize a common problem and try to solve it through pre-existing bodies. This can influence the policy goals, content, instruments but also the policy style. The European Commission acts in this respect²¹, but also the International Monetary Found, the World Bank or the International Energy Agency in some context. In the US, one can think of the FERC which aim is to (i) "Ensure Just and Reasonable Rates, Terms, and Conditions", (ii) "Promote Safe, Reliable, Secure, and Efficient Infrastructure" (iii) "Mission Support through Organizational Excellence".

The fourth string of convergence, *penetration*, is much less voluntary as it consists of "states [being] forced to conform to decisions taken elsewhere by external actors". This mainly refers to influence groups that have an interest in seeing the regulations of different states converge to ease their internationalization. Here again, some would debatably think of the European Commission imposing its decisions on sovereign states. A less controversial example would be the role of the energy lobbies in the regulatory process.

Bennett [1991]'s view highlights the role of stakeholders in the choice of a specific design. Actually, due to their diversity, stakeholders represent the most dynamic element of the process. They have different channels to influence the policy-making: they are active observers of the market, adjusting their strategies based on both local and foreign experience, adjusting to any market signal or change in policy objective. Incumbents and established stakeholders might participate into *penetration*, *harmonization* or even *elite networking*. Consequently, regulation changes might also be impulsed by evolution in the stakeholder structure, bringing new concerns. For instance, operators of non-conventional technologies benefit from more and more attention as their costs lower and as policy objectives increasingly favor sustainability.

Consequently, as time passes by and learning happens, the regulators update their beliefs: the toolbox defined in section 1.2.3 itself slowly evolves. While some features are identified as inefficient and others become consensual, regulatory choices inform on regulators'

¹⁹http://files.brattle.com/files/7431_characteristics_of_successful_capacity_markets_pfeifenberger_spees_oct_2013.pdf accessed on May 8th 2019.

²⁰The APEX mission is to bridge the gap between business education and professional excellence.

²¹Since the first electricity directive of 1996, the European Commission has already passed several additional directives binding to all member states.

beliefs. Indeed, the exogenous factors that limit the relevance of some features are known *ex ante*. However, exogenous shocks like technical change create regulatory challenges that need to be tackled: new features might then appear over time to adjust for an evolving environment. The last years have proven the innovative spirit of new actors in the market and their willingness to solve the energy trilemma as a whole. The impressive learning rates of renewable energies reduce the need for subsidies and create challenges for their competitive introduction in the market under the current framework. Similarly, storage and demand-side flexibility have been struggling to convince that the existing regulation was hindering their development and so limiting *de facto* the ways to improve the SoS. Their grievances have been heard by the FERC who recently (2018) published new directives for storage market integration (FERC order 841). This constantly evolving pool of technologies available on the market creates challenges, justifying the dense interactions with civil society. This both accelerates the flow of information required for learning but also slows down the converging process by generating new issues to tackle as new technologies become competitive and claim their share.

All in all, fitting the different vectors of information into Bennett’s framework shows evidence of learning in the specific case of CRMs. However, this tendency for convergence is continuously challenged by new technologies and business models. These shocks, combined with structural heterogeneity between the systems limit the precision of the information flowing at the international level. As a result, a sequential decision process will account for all relevant vectors of information: the implementation challenge is discussed in the next section.

1.2.5 The implementation challenge: diversity and convergence

As discussed in the previous section, learning does occur from period to period to the benefit of all public authorities (and their populations). This then affects the toolbox that they will consider. Indeed, the CRM that could be imagined in the early 90s has little in common with the designs debated that nowadays. Accounting for both the local specifics (section 1.2.1 and 1.2.2) and the global context (section 1.4.1), this section focuses on the regulatory decision making at the system level through beliefs updating. Public authorities apply their local context to the contemporaneous regulatory toolbox to determine which features are relevant. Then, the final design can emerge once policy objectives and stakeholders’ views are also accounted for. In this sense, learning from our own experience is fully informative, while foreign experience carries imprecise information given the structural heterogeneity between the systems. Such structural heterogeneity hinders the convergence process: (i) it prevents full convergence as some design aspects will remain system-specific, it also (ii) slows down the identification of efficient features.

Indeed, exogenous factors discussed in section 1.2.1 shape the solution space of each system. A large system with sparse consumption centers, like Russia, is more likely to implement locational capacity pricing than a smaller but more densely populated system

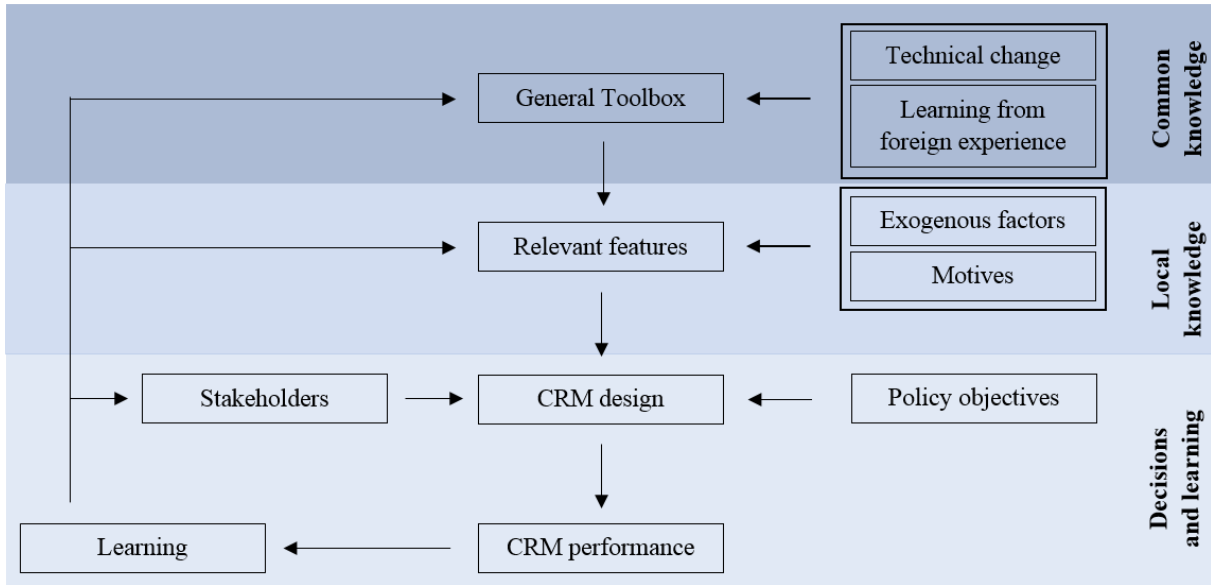


Figure 1.2: Dynamic choice of CRM design

like Belgium. Similarly, a hydro dominated system will see its SoS impacted by the drought to a different extent if it is located near the equator, like Colombia (roughly 70% of hydropower), or around the poles, like Sweden (roughly 42% of hydropower). In the US, "Local electricity grids are interconnected to form larger networks for reliability and commercial purposes"²², the role of the transmission network is thus apprehended in a more integrated way than in Europe where systems usually have the same boundaries as the states themselves. In this sense, the culture and history of institutions matter when considering the options at hand.

In turn, the motives for implementation presented in section 1.2.2 characterize the problem at stake. Even though CRMs will always aim at ensuring a certain reserve margin (in line with the reliability target), the identified market imperfections that motivate the implementation might vary and induce specific regulatory answers. Considering the missing money emanates from inefficient pricing will most likely lead to an attempt to restore the short-term signals, but if the lack of investments is believed to result from the risky environment, then longer contracts might be preferred. The reserve margin can also be temporarily at risk, in which case a less definitive mechanism (strategic reserve) is to be favored. When the lack of demand elasticity is invoked, more attention shall be given to the integration of new technologies, and performance incentives will be carefully considered when the existing thermal generation is getting closer to the end of their lifespan. The chosen design is then constrained, *ex ante*, by the exogenous factors and the motives for implementation, which put restrictions on the solution space.

In this framework, each system can only choose from a limited subset of tools to design the CRM: some features generally considered as "dominant" might be irrelevant, maintaining

²²<https://www.eia.gov/todayinenergy/detail.php?id=27152> accessed on October 22nd 2018.

heterogeneity in the designs implemented. The learning process consequently occurs in slightly different conditions, leading to a slower and partial convergence. The design to be implemented in a specific system emerges from numerous interactions. This helps to rank the features based on their expected efficiency (learning from foreign experience and stakeholders intake) and contextual relevance (knowledge of local constraints).

Figure 1.2 summarizes the interactions leading to a given CRM design. The toolbox presented in section 1.2.3 gathers the regulatory features available to design a CRM. Those features can come from existing or past CRMs, proposals from stakeholders based on own view or foreign experience. For being impacted by the technical change and international experiences, it has a rather slow evolution in time. From this toolbox, it is possible to identify the subset of features relevant for a given system by taking into account the exogenous factors (section 1.2.1) as well as the motives (section 1.2.2). Afterward, more subjective elements are dealt with: policy objectives, as well as the stakeholders' view, reduce the number of features available up to the point that a given CRM design emerges. In turn, the performance of the CRM is used as an input at all stages. New needs might be identified either for CRMs in general (update of the toolbox) or in this specific system (update in the relevant features). Similarly, features may be found irrelevant or inefficient based on experience. Stakeholders also learn from this experience and update their preferences. This local learning usually takes roughly a decade before leading to a revised design.

Chapter A provides an example of such interactions applied to the case of deratings. Indeed, the need to consider firm capacity has been quickly identified. However, two methods for derating (unit specific or technology-wide) kept on coexisting until additional units characteristics became necessary for the valuation of non-conventional technologies.

In sum, section 1.2 has identified the key classes of features that compose CRMs and highlighted the existence of learning in CRM regulation, allowing for the identification of "dominant" (probably efficient) features. This convergence is, however, hindered by the heterogeneity of systems (section 1.2.1 and 1.2.2) and slowed down by exogenous shocks (technological change). The following section proposes to analyze the evolution of CRM design in 10 systems over almost three decades to seek empirical evidence for the framework proposed.

1.3 Overview of CRM implementation

I defend the idea that CRMs are composed of two types of features: the "dominant" (converging) and the tuned (high variance) ones. This dichotomy is in line with the existing separation in the literature. Influenced by standard neoclassic theory, one stream of literature investigates CRM design in a prescriptive dimension, with the underlying assumption that there might exist a universal design superior to the others [Olsina et al., 2014; Mastropietro et al., 2016; Cramton and Stoft, 2005]. Complementarily, another branch of

literature defends that an in-depth analysis of CRM design requires an understanding of system-specific characteristics. This provides useful case studies [Newbery, 1998; Kim and Kim, 2012; Devine and Lynch, 2017; Hancher et al., 2015]. The previous section supplies a unifying framework for the two approaches, which are not only complementary in terms of understanding of the markets but can each be applied to separate sets of features. Cross-system learning allows for the emergence of "dominant" features but system heterogeneity prevents full convergence. This section tests the hypothesis developed in the previous section on a panel of 10 systems. Over almost three decades, exogenous factors, as well as motives for implementation, are highlighted. The consecutive choices in terms of design are analyzed. Such choices are not only discussed at the system level, but common design choices are set out to identify the "dominant" (converging) features.

In the 90s, when CRMs were first designed, regulators picked from a heterogeneous and diverse toolbox. In the absence of learning, the local specifics highly influenced the designs. Historically more market-oriented, the eastern US systems chose quantity and market-based designs while the CRMs implemented in European countries were price-based. This is in line with [North, 1994] who states that common cultural heritage reduces divergence. These differences then disappear over time as dominant features emerge. This section succinctly presents the different designs of the panel in historical order. This is to illustrate the pace of change: a given design choice belongs both to a system-specific context, and to the contemporaneous stock of knowledge. At the aggregate level, three periods emerge: (i) the 90s see the emergence of the first CRMs, (ii) from which the lessons are drawn a decade later with a convergence in the (re-)designs implemented. (iii) Finally, the 2010s draw further the tendency for convergence, but also explicit the coming design challenges - non-conventional technologies integration -. Table 1.7 summarizes the lessons learned from each of the considered regulations and recalls the heterogeneity in exogenous factors and motives that can exist between the considered systems. Along with the introduction of each time period, table 1.7 provides the busy reader with the main takeaways of the section.

1.3.1 The 90s: Experiments

The 90s were an experimenting field for the regulation of emerging electricity markets: little was known on the empirical consequences of liberalization, even less on CRMs. Proposed designs thus strongly relied on economic theory, reminding of a Coase [1960] versus Pigou [1920] dilemma. It resulted in a broad range of designs, all rather simple, seemingly as simple as the problem at hand: ensuring that available capacity exceeds peak demand.

For instance, the first system with a formal CRM is often considered to be the England and Wales power pool when, in 1990, National Grid implemented *ex post* capacity payments in the anticipation of electricity demand growth. Considering the efficiency of the market, it aimed at quantifying scarcity to ensure that the capacity payment gives an investment

incentive as accurate as possible. On 30 minutes time slots, all the capacity participating in the energy market²³ was considered. By the end of the decade, some US systems, as well as the Spanish and Colombian ones, decided to take measures to ensure the SoS. Spain implemented capacity payments to compensate stranded assets: the level of payment then depended on the fuel source and the amount of capacity guaranteed (based on historical availability) by a given generator both in the medium and long-term. The capacity price was determined according to the long-term needs for capacity in the system. Regarding Colombia (1997-2006), it went for a monthly capacity payment following the 92-93 shortages: "Cargo por capacidad" which takes the capital cost of the cheapest technology as a reference (open cycle gas turbines - OCGT). Following FERC order 888²⁴, the US systems started to restructure. In 1998, New England joined the club of cautious regulators by implementing a CRM based on installed capacity (ICAP) with bilateral transactions as well as auctions. A year later, NYISO and the PJM also implemented a similar mechanism. They, however, quickly moved to unforced capacity (UCAP) to avoid over remunerating unreliable units. The common feature of all those mechanisms is their short-term basis: from thirty minutes in the UK to a month in Colombia; it contrasts significantly with the mechanisms implemented later. The only two systems with somewhat long contracts (six month capability period in NYISO and the whole year contract in Spain) figure as exceptions, not only because of this peculiarity but also because they were the only two systems in the panel that never faced structural redesign of their mechanism.

The variety of CRMs implemented in the decade allowed for intense learning, highlighting the importance of availability incentives and the difficulty of fair remuneration of disparate technologies. In Spain, some units would run at a loss to comply with the minimum running hours required for the payment. In addition, the distorting effect of some market characteristics such as congestion and market power had been largely underestimated in those first designs. For instance, market power has been suspected in England and Wales from the beginning in the form of capacity withholding. Newbery [1998] demonstrated evidence of such behavior and the England and Wales power pool²⁵ was reformed from scratch in 2001. From this moment on, no other system has had implemented a full *ex post* payment²⁶. The PJM, ISO-NE, and NYISO also experienced such market power abuse as well as important price volatility.

The main lessons from those first CRMs have thus been threefold: future design should improve the price signal, market power mitigation, and balanced obligations. With respect to the first point, there is a trade-off between the accuracy of pricing, better reached with

²³Day-ahead compulsory pool. The last accepted bid sets the price.

²⁴Issued in 1996, "Promoting Wholesale Competition Through Open Access Non-discriminatory Transmission Services by Public Utilities; Recovery of Stranded Costs by Public Utilities and Transmitting Utilities", <https://www.ferc.gov/legal/maj-ord-reg/land-docs/order888.asp> accessed on March 28, 2019.

²⁵"the restructuring of the pool in 1990 created an effective duopoly in which National Power and PowerGen set the price in over 90% of the time."

²⁶Ireland, and Italy do have/had partial *ex post* component.

short-term mechanisms (which better capture scarcity), and investment incentive that is undermined by the volatility characterizing short-term mechanisms. Those empirical findings, combined with the increased overall knowledge on capacity remuneration, allowed for significant improvements in CRM designs to be implemented in the following decade. This trend resulted in increased attention to the implementation features, while dominant high-level features started to emerge.

England and Wales Pool 1990 - 2001

For being an island, the UK takes the SoS to heart. Fortunately, it benefits from quite some natural endowments: coal and gas, but those resources have historically been located in the North, away from the main populated areas (and consumption areas), which are situated down South. At the end of the 80s, the electricity sector was characterized by a structural need for investment to replace the aging power plants and support demand growth [Rotaru, 2013]. To tackle the issue, the UK became a forerunner in the liberalization of electricity industries. *The Electricity Act* was adopted as soon as 1989 in order to unbundle the sector. The vertically integrated public company was split into three generation utilities; 12 regional distribution companies; 12 regional suppliers, and a transmission operator. The new market organization relied on a compulsory day-ahead pool: the Pool Purchase Price was composed of the system marginal price and capacity payments based on actual scarcity on the market. This will to ensure accurate scarcity pricing reflects strong concerns regarding adequate investments and a form of distrust towards an energy-only market (EOM). The capacity payment would be paid to all generators declared available, irrespective of whether they were actually called. It is based on the Value of Lost Load (VoLL) less the system marginal price. The differential is then multiplied by the actual scarcity estimated through the Loss of Load Probability (LoLP)²⁷ for every half an hour.

The Britain and Wales capacity payments were criticized for being too volatile. They were removed as part of broader market reform in 2001 without capacity remuneration. This is inherent to their nature since they would rely on a very short-term signal. This might provide a very accurate signal on system scarcity and investment needs, but it does not tackle the hedging needs of new entrants. In addition, the VoLL was initially set at 2£/kWh, which was considered as arbitrary by some observers [Von Der Fehr, 1994] or just too high by others. Namely, Newbery [1997] considered that 2£/kWh represented the opportunity cost of a blackout and while insufficient supply is more likely to lead to a brownout, which cost was estimated around 30p/kWh. He also showed that the LoLP tend to overestimate the probability of power failure. Further, the oligopoly structure of the market allowed fruitful withholding strategies [Newbery, 1995]. Such behavior raised the probability of insufficient available capacity (LoLP), mathematically generating higher capacity payments. The pool was thus replaced by a so-called EOM through the New Electricity Trading Arrangements in 2001 (see [Roques et al., 2005] for a complete

²⁷The LoLP is the probability that demand surpasses available capacity.

discussion on the ins and out of each design).

Spain 1997 - 2007

Spain has inherited a large number of hydropower plants from the Franco era with a monopolistic and integrated power system that highly depends on weather conditions. Besides, SoS was a core objective of the government which planned investments for both private and public companies before liberalization [Hancher et al., 2015]. Indeed, given the peninsular characteristic combined with very limited interconnections with neighboring countries, Spain could not count on available foreign capacity in times of scarcity, creating a significant reserve margin. This led to many plants potentially facing difficulties to be profitable in a competitive environment. The First Electricity Directive (96/92/EC)²⁸ which went into force in February 1997 required the unbundling of integrated monopolistic companies [Jakovac, 2012] as well as the separation of competitive activities (production and retail mainly) from distribution and transmission. It also introduced the concept of third party access. The directive did not call for capacity remuneration, but actors in the industry argued that a liberalized power market, especially with regulated prices, would not enable them to recover their investment costs, creating stranded costs²⁹.

The Electricity sector act (ESA 1997) indeed acts on liberalization with an hourly electricity pool based on marginal-pricing with a must offer requirement to any production not already contracted bilaterally³⁰. Considering the existence of stranded costs, the inherited overcapacity as well the cap on the energy market [DG Energy, 2013], it also states that generators *shall*³¹ receive compensation for their contribution to SoS [Hancher et al., 2015]. It seems that the conditions for a functioning EOM were out of reach, and the government went straight away to capacity payments (*garantía de potencia*) without considering alternative designs. The total level of payments was calculated each month based on a fixed price and the demand level of the given month. The amount was then dealt amongst eligible units according to their size and availability during the given month³². Units were subject to minimum running hours at full capacity equivalent³³ and fuel supply constraints to be eligible to the capacity payment [Batlle et al., 2007]. In addition, capacity already committed into bilateral contracts were excluded from the scheme. However, the methods used to set the level of the capacity payment were not made public.

The Spanish capacity payment included an explicit availability condition rare in this

²⁸Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity.

²⁹Costs that companies had incurred before liberalization and which will not be recovered under liberalization due to the shift from rate of return regulation to marginal pricing.

³⁰Actors engaged under bilateral contracting were also excluded from the CP scheme.

³¹A wording replaced by *may* following the 2003 EC directive [Hancher et al., 2015].

³²See http://www.omie.es/files/reglas_mercado_0.pdf p133 accessed on May 10th, 2019 for allocation formulas.

³³The initial requirement was 100h over the past 5 years according to Arnedillo [2004], which was then changed towards minimum requirement over the past year http://www.omie.es/files/reglas_mercado_0.pdf p133 accessed on May 10th, 2019. Hancher et al. [2015] indicates that it was lowered to 50h/year in 2005.

period of experimentation –and maybe unnecessary given the short-term nature of the contemporary mechanisms. However, this availability criteria expressed in running hours proved perfectible. Indeed, some plants would run out of merit so to meet the criteria and to capture the capacity price. For the other, the opportunity cost of the payment was close to zero, meaning that they gave nothing in exchange for the payment [Batlle et al., 2007]. In addition, the opacity of the mechanism resulted in regulatory uncertainty for investors. Indeed, the reserve margin of 20% was useful to meet the quickly growing demand because the high demand for gas turbines worldwide delayed investments until 2002 [Arnedillo, 2004]. In addition, Hancher et al. [2015] argues that grid congestion leads to a number of blackouts in 2001. Those insights suggest a need for further regulatory adjustments so to incentivize investment accurately. However, the room for improvement was tight due to another (financial, this time) drawback in the regulation: under highly regulated end-user prices, the cost of capacity payments was never recovered (neither were other cost components) that created the so-called "electricity tariff deficit". Year after year, the consumers would pay less than the cost of their electricity consumed³⁴, creating a debt to the electricity utilities. Measures to stabilize the deficit were taken in 2002 through a new methodology to calculate tariffs [Arnedillo, 2004], without succeeding in filling it in.

As soon as 2002, Spain started to draw lessons from its regulatory choices, a push towards changes that would be further incentivized by the 2003 Electricity directive from the European Commission. As already suggested, learning takes time, and both were tackled in 2007.

Colombia 1997 - 2012

Colombia is characterized by a hydro dominated power system (around 70%) highly dependant on weather variation. Indeed, most of the dams only have monthly storage capacity [Perez and Chinchilla, 2004]. In addition, the specificity of this region of the world is the occurrence of *El Niño*³⁵ on a cyclic basis (every 2 to 7 years) which reduces the inflows up to 50%. This dry episode is followed by a wet one (*la Niña*). The resulting long-term uncertainty creates a need for large amounts of capacity (empty storages) for a low number of hours on average. The motive for implementation of a CRM is here an inefficient long-term signal due to cyclical weather conditions that create a high uncertainty on thermal generators' revenues, but also creating fertile soil for market power exercise. Besides, the guerrilla lead by the FARC (revolutionary armed forces of Colombia) until recently included attacks to the networks, adding uncertainty on both reliability and plants revenues [Larsen et al., 2004].

³⁴More specifically, households and small businesses would benefit from regulated tariffs below costs.

³⁵"El Niño-Southern Oscillation (ENSO) cycle [...] describes the fluctuations in temperature between the ocean and atmosphere in the east-central Equatorial Pacific" according to the National Oceanic and atmospheric administration. See <https://oceanservice.noaa.gov/facts/ninonina.html> for further details.

The liberalization process of the electricity sector started in the mid-90s in Colombia³⁶, shifting the industry from a state monopoly toward a competitive market [Aramburo, 2012]. It followed the 1992-1993 blackouts that shed light on the need for new capacities -that the government was unable to finance. From the beginning, the SoS has thus been at the core of political concerns due to geographical and cultural characteristics. The *Cargo por Capacidad* followed the implementation of the electricity market (1995) and started operation in January 1997 with the dual objective of ensuring SoS while reducing the market risk for investors³⁷. In this capacity payment, the capacity price was decided by the CREG³⁸ based on the cost of a new open cycle turbine. The price was then fed into simulation and optimization models to define which units were necessary for the least cost generation and system reliability. All of them would receive the capacity payment based on their installed capacity without further requirements [Arango, 2007]. *El Niño* phenomenon occurred right after the CRM implementation (1997-1998). On this occasion, close monitoring of hydro-plants behavior was set by the government, which also paid careful attention to thermal plant pricing and demand rationing (market power mitigation). In parallel, yearly commissioning was encouraged [Frontier Economics, 2017].

However, observers noted that although critical events occur in Colombia during the dry season, most of the payments would nonetheless be paid to hydro plants [Frontier Economics, 2017] at the beginning of the period. Larsen et al. [2004] highlight a shift between 1997 and 2000 towards an increased capacity remuneration of gas and coal plants. The lack of transparency regarding which plant would get the payment added regulatory uncertainty on this revenue. In addition, *El Niño* episode of 1997-1998 brought out suspicion of market power on both the hydropower generators and the thermal ones leading to market power mitigation rules aiming at limiting their bidding freedom either on quantity for the former or on prices for the latter. Despite the shortcomings, the regulator had fixed the duration of capacity payments to 10 years [Frontier Economics, 2017], delaying the redesign to the end of the 2000s.

ISO-NE 1998 - 2006

The ISO-NE (Independent System Operator of New England) was created in 1997, following the FERC³⁹ Orders 888 and 889 that "open transmission systems to fair and nondiscriminatory access and remove obstacles to competition in wholesale trade of electricity"⁴⁰. It is in charge of system operation and transmission organization in Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont, where electric

³⁶Ley de servicios públicos domiciliarios, Congreso de la República de Colombia, 1994a & Ley eléctrica, Congreso de la República de Colombia, 1994b.

³⁷Prior to the *Cargo por Capacidad* was the *Cargos por respaldo de potencia* (1994-1996) which was paid to plants on proportion to their excess of production compared to contractual obligations. It sought to remunerate the plants that were only called in extreme situations [Perez and Chinchilla, 2004].

³⁸Comisión de Regulación de Energía.

³⁹Federal Energy Regulatory Commission.

⁴⁰<https://www.iso-ne.com> accessed on May 9th 2019.

generation historically relied on nuclear and oil. Since then, the mix has evolved towards more gas-fired generation. Previous to restructuring, participants to NEPOOL (New England Power Pool) in New England had a capability responsibility similar to some decentralized CRMs [Fedora and Kazin, 1998]. Promptly following its creation, ISO-NE initiated a monthly installed capability market as of April 1, 1998⁴¹. The FERC indeed approved the wholesale market rules only in December 1998, when the capacity market was already online.

Working in a decentralized way, each LSE⁴² needed to procure a given level of capacity on a monthly basis (its load plus a reserve margin), which would mainly occur through self-supply [Papalexopoulos, 2003] of both supply-side and demand-side units [FERC, 2010]. Participation in the ICAP market of capacity resources within the ISO-NE footprint was de-facto compulsory since the energy of any of those resources could be recalled [Hobbs et al., 2001]. Before the beginning of the ICAP month, bids would have to be submitted to allow for an *ex post* settlement based on realized data. In case of deficiency, the bids submitted *ex ante* were stacked and accepted up to the required quantity: the deficient LSEs paid and the LSEs in excess received the clearing price (given they were cleared) [Cramton and Lien, 2000]. The *ex post* settlement is further described in [Fedora and Kazin, 1998].

Unfortunately, the ICAP market was prone to gaming: it regularly cleared at 0\$/MW until strategic bidding was detected from January 2000: the ISO had to intervene to mitigate the prices that rose as high as 105,000\$/MW [FERC, 2000]. ISO-NE request to terminate the ICAP market was supported by Cramton, who argued that the marginal cost of capacity in this market was zero and thus unnecessary [Cramton, 2000]. Both already suggested the superiority of a forward capacity market in sending accurate price signals; ease entry and reduce volatility⁴³. FERC agreed on the elimination of the monthly auction as of August 2000, leaving bilateral contracting and self-supply as the only option to comply with their obligation. An administrative penalty came as a replacement to the compulsory adjustment auction⁴⁴ until the new monthly supply came into force in April 2003. Even then, only a small share of total capacity was procured through auctioning (around 5% in 2003 according to ISO-NE [2004]).

In the absence of locational prices for capacity (locational energy prices were implemented in 2003), this capacity market failed to send efficient scarcity signal: aggregate overcapacity and low capacity prices pushed necessary units located in constrained regions out of the market. Consequently, "Reliability Must Run contracts" (or "reliability agreements")

⁴¹ Actually, it was completed by a Daily Operable Capability market which was removed in March 2000 due to gaming, raising prices to price cap although the product exchanged had no opportunity cost and was not used in dispatch [FERC, 2000] p81.

⁴² Load Serving Entities.

⁴³ http://www.energymarketers.com/Documents/ISONE_Reliability_Assurance_Mechanisms.pdf accessed on May 20th, 2019.

⁴⁴ <http://lmpmarketdesign.com/papers/HardCopyMasterVersion-8-31-2015-capacity-workshop.pdf> accessed on May 20th, 2019.

were developed to prevent those uneconomical units from decommissioning⁴⁵ [Chandley, 2005]. The FERC rejected the broad use of such contracts. It also argued in favor of a locational component in the capacity market as soon as 2003-2004, confirming the need for a long-lasting design. A Locational ICAP was developed as of 2004 and accepted, but the long-term objective remained the implementation of a forward capacity market. Extensive discussions with the stakeholders were conducted, resulting in several FERC filings between 2004 and 2007. To smooth the transition from short-term incentives to long-term incentives, fixed capacity payments were set up between December 2006 and May 2010⁴⁶ while the first auction of the Forward Capacity Market (FCM) took place in 2008 for the delivery year 2010-2011 [River Associates, 2017]. Sometimes disregarded (as for the GB capacity market in 2014), the choice for a transition mechanism reveals an effort to ensure a form of continuity in adequacy support while trying to limit gaming.

NYISO 1999 - to date

Replacing the New York Power Pool (NYPP) that had already been coordinating state-wide wholesale power⁴⁷, the New York Independent System Operator (NYISO) came into operation following the FERC orders 888 and 889 in December 1999. The capacity market was launched as of the same winter (1999-2000). NYISO includes diverse geographical situations. Specifically, it is in charge of Manhattan that bears an obvious strategic role for the country with limited space to build the plants necessary for its own SoS. In parallel, NYISO also encompasses less populated areas. Although counting with significant nuclear capacity (roughly 30% of generation), it is a net importer that borders four systems of which half operates a capacity market.

The NYISO capacity market is a short-term one. Indeed, the level of load obligation is estimated and passed on by the transmission owners to the system operator (NYISO). In turn, it processes the data provided, accounting for the yearly defined reserve margin and eventual locational requirements⁴⁸ before providing each LSEs with its ICAP obligation [NYISO, 1999]. The notification is followed by a 30 day trading period at the end of which LSEs and ICAP suppliers⁴⁹ are required to provide a certification form. Would there be any deficiency from an LSE or a unit, they would have to pay a locational deficiency charge. NYISO capacity market differentiates two capability periods: summer (May to October) and winter (November to April). Capacity can be purchased or offered either bilaterally or on one of the two-sided forward auctions. The reference auction is the capability auction that is organized thirty days before the beginning of the capability period and considers the six months at once. The monthly auction then allows the actors

⁴⁵PJM actually had similar contracts previous to the RPM reform.

⁴⁶Le level of payments can be found in the following FERC order and are adjusted for a weighted forced outage rate <https://www.ferc.gov/CalendarFiles/20061031182054-ER06-1465-000.pdf> accessed on May 20th 2019.

⁴⁷NYPP was created in 1969 in response to the 1965 blackout in order to prevent new occurrence.

⁴⁸Locational requirements forces LSEs that operate either in Long Island or in Manhattan to procure part of their obligation from capacity within the constrained areas.

⁴⁹Existing and planned.

to adjust their positions for the remaining of the capability period fifteen days before the beginning of each month. Ultimately, two days before the beginning of a given month, NYISO organizes the spot market auction where it centrally⁵⁰ procures the potentially missing UCAP for the following month on a locational basis (deficiency auction) [NYISO, 2019].

One specificity of NYISO, over all other systems, is its regulatory consistency. The design described above has little changed since then. Moving along with the increasing knowledge accumulated on CRMs, NYISO has been able to improve its mechanism incrementally – and avoid a full redesign. Mainly, nodal prices were implemented in 2000 and unforced capacity in 2001⁵¹, the demand curve of the spot auction became sloped as of 2003 to mitigate price volatility while mitigation rules to discourage entry came into force in 2007 along with several additional nodes. The unforced capacity derates the ICAP (installed capacity: maximum ability to generate) to account for forced outages and to secure actual firm capacity. A system-wide average derating adjusts LSE’s minimal ICAP requirements while generators see their capacity derated on a unit basis according to their 12 months performance [Chao and Lawrence, 2009]. UCAP can then be traded through the different auctions in place [Grottoli, 2017]. In exchange for their capacity remuneration, capacity suppliers are required to provide NYISO with performance data⁵² and bid on the day-ahead market.

All in all, NYISO has been able to build a CRM able to last over time where, as this section will highlight, most CRMs require a redesign every decade. One could argue that NYISO is a particular case because its footprint only spreads over the state of New York, while its American counterparts often have to deal with various state-specific regulations. This explanation, however, disregards the international experience where system operators’ footprints often overlap the national territories (homogeneous regulations).

PJM 1999 - 2007

The history of PJM started in 1927 when three utilities decided to benefit from economies of scales by joining forces in a power pool, but the PJM was officially created in 1962 when additional utilities joined. It is only in the 1990s that PJM transitioned to become an Independent System Operator (ISO) in 1997 and a Regional Transmission Organization (RTO) in 2002. The FERC orders 888 and 889 also led to restructuring in Pennsylvania, New Jersey, and Maryland, where PJM started operating an electricity market with nodal pricing in 1998. With a footprint spreading over numerous states, the PJM has to adjust to different local realities: states not only have different natural endowments leading to

⁵⁰Refer to <https://www.nyiso.com/documents/20142/5624348/ICAP-Translation-of-Demand-Curve-Summer-2019.pdf/e1988852-3fcf-281c-4ac7-dff12d078507> and <https://www.nyiso.com/documents/20142/2953344/Demand-Curve-2019-2020.pdf/fbe06a61-0578-d056-5c78-dfab5b9ae74b?t=1542819100565> accessed on May 9th 2019 for further details on the current administrative demand curve (2019).

⁵¹The auctions are, however, still called ICAP auction, even though unforced capacity is traded.

⁵²See attachment K of the ICAP manual https://www.nyiso.com/documents/20142/2923635/app_a_attach_icapmn1.pdf/503354b6-0607-9a12-f2d4-f866c25eac65 accessed on May 9th 2019.

different policy preferences (and mix)⁵³, but they also have large prerogatives over retail, generation and distribution regulation.

The obligation to secure the load was anterior to PJM creation [Hobbs et al., 2001] as an ISO: historical institutions justify the implementation of a CRM (although market-based motives were identified later on). However, after restructuring, entering LSEs accused the existing obligations to deter entry because it favored integrated utilities: the obligations were annual, which was deemed not flexible enough in a context of load switching retailers, and capacity obligations had to be procured on a bilateral basis to integrated utilities [Bowring, 2013]. This led first to regulatory intervention in Pennsylvania and then to the creation of a mandatory market in 1999 to foster competition.

The capacity market in PJM thus aimed at the efficient procurement of capacity: the objective of the daily obligation was to allow the LSEs to adjust for their portfolio evolution (clients switching retailer). Conditions to provide capacity included a day-ahead energy market offer⁵⁴, deliverability within the PJM and outage reporting⁵⁵ [Bowring, 2008]. In exchange for capacity remuneration, the primary commitment of cleared capacity is actually the possibility to be recalled (provide energy) at prevailing energy prices in case of capacity shortages [Creti and Fabra, 2007]. In terms of deratings, the ICAP (nameplate capacity) was tested in summer and winter. Then, the EFORD⁵⁶ was applied to get the unforced capacity (UCAP). In fact, [Papalexopoulos, 2003] states that PJM was the first to consider capacity on an unforced basis. On the demand-side, LSEs had to contract the equivalent of their coincident peak scaled for active load management and the administrative reserve margin in terms of installed capacity. The obligation was issued 36h in advance so they could resort to self-supply, bilateral contracts or capacity market auctions to comply with their obligation [CIGRE, 2016] if not already secured in the monthly or multi-monthly auction. A failure to procure sufficient capacity induced a penalty (capacity deficiency rate).

However, as highlighted by [Bowring, 2008], PJM is structurally prone to market power exercise⁵⁷. Market power abuse (bids at the opportunity cost - deficiency rate), as well as arbitrage opportunities with the energy market (exports⁵⁸), led PJM to change the market

⁵³<https://www.pjm.com/~media/library/reports-notice/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx> (accessed on May 14th, 2019) graphs pages 11-13 show broad local disparities in terms of mix and a significant share of nuclear generation in the PJM.

⁵⁴The obligation was removed in 2001 since capacity owners could bypass the underlying availability constraint through artificially high bids (unlikely to be dispatched).

⁵⁵Used to determine unforced capacity.

⁵⁶Demand Equivalent Forced Outage Rate: "The portion of time a unit is in demand, but is unavailable due to forced outages" according to the PJM definition.

⁵⁷"Given the basic features of market structure in the PJM capacity market, including the existence of pivotal suppliers, inelastic demand, tight supply-demand conditions, the relatively small number of non-affiliated LSEs, the capacity-deficiency penalty structure facing LSEs, supplier knowledge of the penalty structure, and supplier knowledge of aggregate market demand, if not individual LSE demand, the potential for the exercise of market power is high." [Bowring, 2008].

⁵⁸The year 2000 was characterized by shortages due to generators preferring to export than bidding into the PJM [Bowring, 2008]. See also [Hobbs et al., 2001].

rules in 2001. It sought to favor transactions in monthly and multi-monthly markets, instead of the daily market, to incentivize both LSEs and suppliers to buy and sell on a seasonal basis. Yet, the price signal could not be fully restored under this market design due to locational constraints inconsistent with a unique capacity price. In addition, market revenues were regularly pointed as too low for investment costs recovery [Monitoring Analytics, 2008], and the volatility of a daily price is not likely to promote competition from new entry. Acknowledging the limits of the design in units' performance as well as investment incentive and market power mitigation, the transition towards the forward capacity market initiated in 2007. Indeed, the first explicit market power mitigation rules only appeared with the RPM reform in 2007.

1.3.2 The 2000s: Learning and popularization

The 90s decade has seen the implementation of a broad variety of rather simple designs that were identified as faulty in terms of performance incentives and market stability by different actors. This resulted in significant learning on CRMs. The main challenges were to improve the price signal, mitigate market power and improve the obligations. With respect to the first point, locational prices have been increasingly used to account for congestion. Besides, the contract duration (both lag and delivery period) increased to stabilize the income and limit opportunistic bidding. This is to the expense of accurate scarcity remuneration. The sloped demand curve also limits price volatility while reducing market power. Obligations and deratings became more complex to account for market reality.

However, learning takes time, so those improvements mainly occurred at the end of the 2000s, making Italy is some kind of an outlier in our timeline. Indeed, Italy implemented temporary capacity payments in 2004 because of the 2003 blackouts which acted as an exogenous shock on their arbitrage with respect to the energy trilemma. The amount of the payment was calculated partially *ex ante* (€/kWh), but also included an *ex post* component (€/MW).

The second group of implementations/reforms occurred at the end of the 2000s. Ireland has had a capacity payment implemented since 2007. The market operator calculates the missing money of a new peaker, which, multiplied by the available capacity at peak, makes the total sum of capacity payment. This amount is then redistributed amongst generators depending on: their forecasted availability, their participation to LoLP reduction as well as their realized contribution to the latter. Colombia also changed its CRMs towards a forward call option on energy. The contract is financial with physical back-up, meaning that the amount of capacity contracted has to exist, but it will be activated based on energy price levels (as scarcity indicator). In MISO, a transitory decentralized capacity market emerged: LSEs self-assess their future peak demand. The system operator uses those forecasts to calculate the capacity target, but they also serve as a reference for the obligations. The PJM reformed the ICAP through the RPM reform in 2008. The latter

included a forward period, an annual sloped demand curve, the EFORD (probability to be available when needed) was used instead of plain capacity [Batlle and Rodilla, 2010] (as already done at the beginning of the 2000s). This also came with nodal prices and the obligation to produce. 2010 was the year in which ISO-NE was reformed similarly: a three-year forward period, descending clock auction (instead of self-supply), as well as a different status for new-built capacity. NYISO had already implemented some of these changes⁵⁹, little by little, since the beginning of the 2000s.

Already, similarities appeared between the implemented designs. Various challenges also emerge. Indeed, US designs moved towards longer contract durations and improved capacity price signals through volatility reduction (sloped demand curve) and locational pricing. Although northeastern US designs are similar with this respect, the Italian scheme also considers a locational component and Colombia set a forward-looking design. The most obvious challenge regards the integration of new technologies. Indeed, the improvement of demand response and storage technologies has created a space for them in the market. In the quest for market-based profitability, they have claimed their contribution to SoS and their desire to be fairly remunerated for that. This is a game-changer in the sense that it brings out a new kind of key feature: verification. Indeed, the production of conventional generation equates its contribution (one way). Units that can both consume and produce, such as DR and storage, require additional verification to make sure they behave accordingly to their obligations. Then, market power mitigation is a never-ending objective; the innovations in market power expression always require new ways to mitigate. Finally, the hybrid capacity payments implemented in Ireland and Italy were deemed unsatisfactory with respect to the price signal, which called the decline of capacity payments. The inertia of regulation also appears in the delay between the identification of design failures and the actual reforms.

Italy 2004 - to date

The Italian power sector was liberalized in 1999 with the *Bersani decree* implementing the EU Electricity Directive (1996): unbundling of generation, transmission, and distribution. This was assorted with competition in production as well as in retail for big consumers⁶⁰. Italy is characterized by its geographical position that favors the emergence of bottlenecks⁶¹, but also its dependence on imports from the North⁶². Although the well-known blackout of September 2003 set the light on Italy's dependence to imports⁶³, [Benini et al., 2006] argues that "the problem of resource adequacy" became very hot in Italy in June 2003 when the TSO was forced to order rolling blackouts, due to insuffi-

⁵⁹Nodal prices, UCAP, and sloped demand curve.

⁶⁰Full retail competition was only required later by the 2003 EU Electricity directive.

⁶¹Italy is composed of 4 price zones plus Sardinia and Sicily.

⁶²More than 10% of its total demand has been covered through imports over the past decades. The International Energy Agency estimates that Italy imported 16% of its consumption in 2016. The situation has been inherited from the pre-liberalization period when long-term contracts with French and Swiss producers were common.

⁶³See [UCTE, 2004] for a detailed analysis of the causes of the blackout.

cient available generation capacity and high summer loads". In any case, the government decided to take a stand in favor of capacity remuneration to overcome the capacity gap⁶⁴. A hybrid capacity payment was implemented as soon as 2004 in order to keep old plants online and foster new investments. This so-called "temporary" mechanism ended up lasting more than a decade. The 2003 blackout acted as an exogenous shock where Italy had to quickly take action and did not have time to harvest all the ongoing learning and rather implemented a temporary scheme.

The payment was granted on a daily basis to all thermal generators that make their capacity available on critical days. Foreign plants or non-programable plants would not be eligible for this capacity payment. Eligible plants would receive the payments on a daily basis, which amount would vary depending on the actual scarcity, their location, and also the opportunity cost of the plants [Hancher et al., 2015]. Indeed, an *ex ante* component of the payment (€/MWh) would be set every day for the next day, depending on the scarcity foreseen for each hour [DG Energy, 2013]. The envelope from the collected fixed capacity charge would be dealt based on availability and estimated scarcity to hedge consumers against high capacity prices: the total capacity revenues could not exceed the amount available. Then, an *ex post* component (€/MW) would be added if the average day-ahead price over the day fell below a pre-defined level⁶⁵. This component is oriented towards generators that would be protected against low energy prices: it basically remunerated their opportunity cost.

According to [Benini et al., 2006], the payment would not cover the fixed and investment costs of gas turbines. Consequently, the payment might effectively delay plants' closures but would be unlikely to stimulate new investments. This idea is explored by [Hancher et al., 2015] who argue that the Italian experience highlights the compatibility of CRMs with a structural dependence on imports as part of the least-cost system. In the case of Italy, the capacity payments were to be removed as soon as a more elaborate and consensual CRM could be voted. In 2011, the energy regulator (AEEG) justified the need for capacity remuneration by both regulatory and market imperfections. Regularly changing regulation creates uncertainty for investors, but market imperfections include the high volatility of revenues disincentivizing investment, as well as information asymmetry impeding investment coordination between generators and the system operator (SO), leading to investment cycles (see also [Terna, 2015]).

The Italian case is characteristic of regulatory inertia. Indeed, discussions about the next design took time due to various back and forth between the different stakeholders (the regulator, the SO, the government, the European Commission, and the market actors)⁶⁶

⁶⁴Decree of the 19th December 2003.

⁶⁵based on the pre-liberalization administered tariff.

⁶⁶Timeline of the design of the final CRM [CEER, 2006; Terna, 2015]:

2005: First consultation document on a reliability option scheme - rejected by the majority of generators.

2008-2010: 4 public consultations on CRM.

2011: The regulator publishes the principles of the CRM and mandates the SO (Terna) to design the CRM.

2012: The regulator satisfied with the proposal.

even though reliability options have been rather consensual since the mid-2000s.

Ireland 2007 - 2018

The Irish capacity payments have been introduced simultaneously to the Single Electricity Market (SEM). Starting in 2007, it gathers the two previously existing markets on the Island. The contractual objectives of the SEM were least-cost and reliable electricity supply both in the long and the short-term. It was regulated jointly by the Commission for Regulation of Utilities (CRU) and its counterpart in Belfast, the Utility Regulator. The period 2003-2006 was characterized by an increasing internal demand in the context of insularity, raising concerns with respect to the SoS. Indeed, Ireland adopted a temporary reserve⁶⁷ in 2004 in prevision of a capacity gap expected as of 2005. In addition, the SEM implemented in 2007 was a mandatory pool with short-run marginal cost bidding. Such a market design is unlikely to solve investment incentive problems since generators would have been unable to recover their full costs within the wholesale electricity markets [European Commission, 2017].

Similarly to the Italian capacity payment, the Irish scheme was a two-sided payment composed of an *ex ante* and *ex post* component (plus de fixed one). First, the Annual Capacity Payment Sum (ACPS) was the pot that sums the capacity charge levied from the consumer on an annual basis. The amount collected resulted from the capacity requirements (amount of capacity considered as necessary to meet the reliability criteria) and cost of new entry (CONE)⁶⁸. The ACPS is then split into monthly envelopes (monthly Capacity Period Payment Sum) proportional to load levels. In turn, the monthly capacity period payment sum was divided into three separate components. A fixed share, the Fixed Capacity Payments Proportion (FCPP) was defined at the beginning of the year based on demand forecasts. In addition, the *ex post* Capacity Payment Proportion (ECP) fixed the part of the monthly envelop to be distributed based on *ex post* Loss of Load Probability (LoLP) in each Trading Period (30 minutes). Per construction, the amount of payment from the ECP was defined at the end of the relevant month. Complementarily, the last component (Variable Capacity Payment Proportion - VCPP) was rooted in the forecasted LoLP of each trading period. Historically, the respective proportions have been

2013: Detailed proposal opened to public consultations followed by the approval of the regulator.

2014: Green light from the ministry.

2015: Engagement of discussion with the EU to get clearance for the scheme.

2018: Approval of the European Commission.

⁶⁷"Ten years long Capacity and Differences Agreements (CADA) would be granted to generators that would undertake the construction of this new generation capacity". The CADA worked as "call options" in the sense that generators received a capacity payment and paid back the scarcity rent to the TSO (the positive difference between the spot price and the strike price). It was financed through a levy imposed on consumers (based on their subscribed connection power) and had only been granted to two generation plants totaling 560MW. See http://ec.europa.eu/competition/state_aid/cases/137628/137628_485545_28_2.pdf and https://ec.europa.eu/energy/sites/ener/files/documents/20130207_generation_adequacy_study.pdf accessed on May 7th, 2019.

⁶⁸The CONE was based on the best new entrant (BNE): an Alstom GT13E2 with distillate fuel in Northern Ireland, the ACPS reached €529 million in 2013.

0.3 for the ECPP and FCPP while the VCPP was set to the remainder (0.4). From this general key of allocation, each generator would receive the payment indexed on expected LoLP (FCPP and VCPP) or realized one (ECPP).

For most observers, the performance of the Irish scheme was satisfactory [CIGRE, 2016]. For instance, according to [CER, 2013], the *ex post* payments (ECPP) were able to send an accurate scarcity signal for being high at time of low margin. For instance, wind generation had a depressing effect on *ex post* payments (ECPP) due to the contingent LoLP reduction. The *ex ante* component, (VCPP) was more dependant on the load as a driver of the forecasted LoLP and could be influencing future trading arbitrage, especially on interconnectors. Naturally, the fixed component (FCPP) acts as a revenue stabilizer. However, improvements could be foreseen: the high proportion of *ex ante* payments led to an over-remuneration of intermittent generators and inefficient market exit [DG Energy, 2013]. Besides, a 2011 Pöyry report for CER and NIAUR⁶⁹ argued that the relationship between the payment and the LoLP could be stronger. In the same report, fluctuations of the total sum collected are suspected of creating uncertainty for new entrants while a separate study⁷⁰ considers the payments not to reflect the actual fixed costs of the new entrants in the market. Nevertheless, the usefulness of understanding this Irish scheme for other systems is limited: the short-run marginal cost bidding in place at the time is less and less implemented.

Spain 2007 - to date

In 2007, a substantial revision of the capacity payment was implemented following the revision of electricity tariffs. They officially relied on the public good characteristics of SoS (inelastic demand, significant grid constraint and insufficient electricity price to incentivize investment) [Hancher et al., 2015], but three additional elements help to understand the timing and the content of the measure. Indeed, the previous CP from 1997 presented the common drawback of inadequate availability incentives. In addition, the "electricity tariff deficit" had not been eliminated and the compensation for stranded costs could only run until 2008⁷¹. Capacity payments are then allocated according to an "availability service" in the medium and long-term capacity contracts for new entrants [Comisión Nacional de la Energía, 2007]. The new design is optional and accounts for bottlenecks. Long-term availability is an incentive for investments in new generation units, the remuneration level is defined in line with the long-term capacity need: the *markets and competition commission*⁷² decides exogenously of the long-term capacity price according to a capacity price curve and the expected reserve margin. The actual level of investment is left to the market [Hancher et al., 2015]. They are only granted to new projects. The payments for medium-term availability aim at securing capacity up to a one-year period, it can

⁶⁹<https://www.semcommittee.com/sites/semcommittee.com/files/media-files/SEM-11-019a%20CPM%20Review%20Appendix%201%20-%20Poyry%20Report.pdf> Accessed on November 15th, 2018.

⁷⁰<http://wattics.com/the-electricity-market-in-ireland/> Accessed on November 15th, 2018.

⁷¹European commission, Decision SG D/290553 of July 2001, *Spanish Stranded Costs*.

⁷²*Comisión Nacional de los Mercados y de la Competencia*.

be assimilated to some kind of reserve. The scarcity periods are clearly defined, and significant penalties for non-delivery are determined. The plants having this availability for service with *Red Eléctrica de España*, the system operator, might have to produce at loss (out of the market).

Against the international flow, Spain made its CRM more and more targeted as a way to reduce the SoS costs in the context of budget tensions. Indeed, the Spanish consumers could benefit from a regulated tariff which had not increased in correlation with costs according to observers, leading to an accumulated deficit⁷³. In addition, the economic crisis led to a demand growth lower than expected, and overcapacity emerged on the market. As a result, marginal changes were made to the system in 2011-2013 to remunerate the plants which are actually increasing reliability, with the primary objective to prevent de-commissioning. Long-term capacity payments were suppressed for new projects⁷⁴ and also reduced for existing plants against an extension of the contract period as of 2012-2013. Again, this evolution would be in opposition to EU regulatory developments if it is the not beginning of a phase-out –or redesign. Indeed, France was urged to complement its design implementing long-term contracts for new built while the British mechanism is being criticized on the basis of discrimination between the technologies (see the corresponding sections).

PJM: Reliability pricing model (RPM) Reform 2007 - to date

Market power, as well as price volatility, were identified as significant drawbacks from the short-term ICAP market. In addition, [Joskow, 2007] showed that an optimally dispatched new peaking turbine would have been able to recover its annualized investment in no year in the period 1999-2005 (considering energy plus ancillary services revenues). To reduce revenue uncertainty, a yearly commitment (from June to May) combined with a three-year forward period was considered appropriate [Bowring, 2008]. However, a transition period was implemented between 2007 and 2011 to maintain a form of continuity between the two market designs. The forward period is gradually increasing from the short-term one in 2007 to three full years in 2011. In the RPM, the procurement is centrally defined based on a reliability criterion of 0.1 loss of load probability and the net CONE of a peaking unit, resulting in an annual kinked (concave) demand curve. When the transmission constraint zone is identified before the auction, a separate demand curve is calculated. However, a separate clearing is also carried out if significant price differences emerge during the auction due to transmission constraints. In 2017, 27 locational delivery areas co-existed. Three kinds of auctions are proposed: (i) The base residual auction (BRA) that takes place three years before the delivery year with a central buyer. (ii) The incremental auction adjusts for procured capacity, it refines positions for agents and elaborates a finer quantity target for the regional transmission operator (RTO). (iii) The third kind of auction is the

⁷³https://cincodias.elpais.com/cincodias/2016/12/16/empresas/1481902389_675893.html, last accessed on January 11th, 2019.

⁷⁴Starting operation after 2015.

continuous incremental auction which only takes place if needed.

A great diversity of resources are allowed to participate in the market: existing generation units, planned generation units as well as transmission investments⁷⁵, demand response and energy efficiency. To account for the accurate contribution to system security, the ICAP is derated thanks to the EFORD (estimated forced outage rate⁷⁶) to get the unforced capacity (UCAP) to be auctioned. The EFORD is derived either from GADS data (Generator Availability Data System that units are bound to share with PJM⁷⁷) or Class Average Outage Rates which is published monthly by the PJM (in case GADS data are unsufficiently available). Considering the identified limits of the ICAP market, obligations, verification, and penalties have benefited from special attention. For instance, linking the EFORD to actual or even past availability is an incentive to perform and be available to maximize future revenues.

With respect to the obligation, payments are linked to the performance of physical units; they are bound to offer on the day-ahead market and energy is recallable in case of scarcity [Bowring, 2013]. Several verification means are designed. The commitment compliance aims at verifying the UCAP. The peak hour period availability for non-variable generation checks historical availability over 500 hours. In addition, a seasonal capability testing assesses the maximum generation. For the demand-side units, the load management event compliance values the compliance with the signal from RTO. Complementarily, the load management test compliance is initiated by the supplier directly. Once the performance is assessed, the penalties collected from underperforming units are dealt to overperforming ones.

Market power mitigation plays a great role in the RPM design with must-offer requirements and unit-specific offer caps when there is no new entrant in the zone. A test for three pivotal suppliers is implemented to assess the degree of market power in each zone. If failing the test, pivotal buyers shall bid at the marginal cost of capacity (see [Bowring, 2013] for further details). On the contrary, there is a Minimum Offer Price Rule (MOPR)⁷⁸ to prevent subsidized units from pulling capacity prices down, distorting the price signal and potentially creating missing money for non-subsidized plants. In addition, a special case is made for the new units built in relatively small constrained areas because it structurally creates oversupply in the given zone, depressing capacity prices for the future. They can thus obtain multi-period contracts where their capacity price is secured for up to three years; in exchange, they cannot bid at or below their clearing price during the reference period.

⁷⁵If it reduces the inter-zone congestion. Otherwise, they can opt for the rate of return remuneration.

⁷⁶Probability to be available when needed.

⁷⁷Required by PJM and North American Electric Reliability Corporation (NERC) reporting standards. Cf <https://www.pjm.com/markets-and-operations/etools/egads.aspx> accessed on November 16th, 2018.

⁷⁸See [Bowring, 2013]. The current one (May 2019) is pending due to FERC rejecting proposals of MOPR changes while considering the current one as "unjust and unreasonable" (2018). see <https://insidelines.pjm.com/2018-in-review-markets-prove-value/> accessed on October 8th, 2019.

On the demand-side, participation is mandatory for the LSEs. The ISO procures most capacity on their behalf. However, integrated companies can secure their resources on the Fixed Resources Requirements (FRR)⁷⁹. In exchange for central procurement, all LSEs have to pay the equivalent of their daily unforced capacity⁸⁰ obligation which is driven by their weather normalized peak load [River Associates, 2017]. The cost is passed through to consumers via retail tariffs. Contrary to the previous design, load management cannot be used as capacity obligation reduction but need to compete on the supply-side [Bowring, 2013].

While the RPM reinforced performance incentives and market power mitigation compared to the ICAP market [Batlle and Rodilla, 2010], an improvement margin remained. River Associates [2017] identified several issues within the RPM. (i) non-performance would not automatically lead to capacity remuneration cancellation, which was commonly considered as a poor incentive to perform. This partially explains why the winter 2013-2014 registered records in both peak load (8 out of 10 max days) and technical outages in the PJM (22% of total installed capacity on January 7th, 2014), 25% of them caused by fuel supply problems (frozen coal or lack of gas or fuel) [Carson and Davis, 2014].

The shortages of winter 2014 lead the PJM to change the capacity product towards the so-called "capacity performance" (approved by FERC in June 2015). As a transition, the two products have coexisted: the base capacity (former product) and the capacity performance, to later only procure capacity performance. Under this framework, cleared resources have to produce when the PJM declares an emergency situation⁸¹, their performance is assessed each hour declared as emergency (performance hours), this makes capacity performance a daily product by nature. Failure to perform is penalized under a quasi "no excuse" rule. In addition, penalties have been reformed to punish underperforming resources (given their capacity was committed and their performance ratio below system average) and reward overperforming ones (all units -committed or not- with a performance ratio above system average)⁸². Of course, the performance can be contractually shifted to another non-resource (a form of secondary balancing market [CIGRE, 2016]).

In addition to the improvement of performance incentives, (ii) the demand curve was changed towards a convex one in 2014 due to the incapacity of the previous version to accurately reflect the marginal value of reliability and meet the reliability criteria (tendency to under-procure). (iii) New technologies also created unexpected challenges

⁷⁹The FRR allows the LSEs to self supply their peak demand, but it has to contract the resource for five delivery year at once. The resource (capacity) will not be allowed to participate in the RPM in the meanwhile nor benefit from the penalties re-allocation.

⁸⁰The PJM defines the Obligation Peak Load as "the daily summation of the weather-adjusted coincident summer peak, last preceding the Delivery year, of the end-users in such Zone, for which such Party was responsible on that billing day" [PJM Interconnection L.L.C., 2010].

⁸¹See the 2018 PJM report on *Strengthening Reliability: An Analysis of Capacity Performance* <https://www.pjm.com/-/media/library/reports-notices/capacity-performance/20180620-capacity-performance-analysis.ashx?la=en> accessed on October 8th, 2019.

⁸²<https://www.pjm.com/-/media/committees-groups/committees/elc/postings/20160505-performance-assessment-hour-education-presentation.ashx?la=en> accessed on May 16th, 2019.

with the suspicion of speculative behavior from the demand-side, which is only allowed in the market as on the supply-side. (iv) The MOPR is currently unsatisfactory, but the situation should be resolved in the coming months. With this analysis, it appears clearly that the RPM has been revisited following the 2014 shortages through changes in the demand curve, the capacity product (increased obligations and penalties, simplified verification), and market power mitigation. However, such adjustments have not required a profound redesign of the market itself, meaning that the current high-level features are emerging as "dominant".

MISO 2009-2012

MISO (Midcontinent Independent System Operator) now spreads over 15 US states from Louisiana down South, up to Michigan and Montana, even including the Canadian province of Manitoba. Since its creation in 2001, its large footprint creates regulatory challenges to make the ISO regulations in line with the state-specific ones. Indeed, MISO is the only US ISO that did not emerge from a pre-existing pool: market operations (energy and transmission rights) only date back to 2005 and ancillary service to 2009⁸³. It includes states with different degrees of liberalization, unbundling and competition. An important driver of adequacy regulation is the divergence of opinions among stakeholders: regulated vertically integrated firms can hardly have the same preferences as LSEs under retail competition. This diversity in the industry organization is an exogenous factor leading to different regulatory possibilities.

The long-term resource adequacy construct was approved in 2007 by the FERC. It replaced the 2004 transitory resource adequacy plan [Newell et al., 2010]⁸⁴ that had been implemented following the August 2003 blackout⁸⁵. It defined LSEs capacity requirements. The long-term resource adequacy construct implementation was finalized in 2009: it included monthly self-estimated UCAP requirements that could be met either through self-supply, bilateral contracting or voluntary residual capacity market.

MISO conducted a LOLE study (1-in-10 year target) on an annual basis from which is derived the planning reserve margin (PRM) for the whole system⁸⁶. The PRM was then adjusted for non-coincident peak load and system-wide forced outage rate, so to have the PRM requirement (PRMR). Each LSE then applied the PRMR to its forecasted non-coincident peak load to obtain their self declared requirements in terms of UCAP. They

⁸³<https://www.ferc.gov/market-oversight/mkt-electric/midwest.asp> accessed on May 16th 2019.

⁸⁴Since MISO did not have markets pre-existing its creation, the transitory resource adequacy plan was implemented not to put reliability at risk in the implementation phase. Actually, the EOM construct seems to have had the preference of MISO in the early days, but after several years of consultations with stakeholders (see [FERC, 2006b] and [FERC, 2007]), it appeared that decentralized reliability requirements would better fit the characteristics of MISO, dominated by vertically integrated utilities (see [FERC, 2008]).

⁸⁵Caused by mismanagement of the consequences of a tree contact with a power line that went out-of-service (see [U.S.-Canada Power System Outage Task Force, 2004]).

⁸⁶This PRM is indicative, any state could decide to fix a different reserve margin. Contrary to other systems, MISO did not make any adjustments to compensate for such an occurrence.

also had to disclose the methodology used to calculate their peak load forecast as well as enough data to determine the variance around the forecast. Indeed, MISO checked for under-forecasting through statistical means, comparing the normalized realized peak load to the forecasted one. When deemed under-forecasting, LSEs could avoid the penalty if they were able to show that an unexpected event had occurred. A second reason for a LSE to face a penalty was under-procurement; such penalty was a non-linear multiple of the gross CONE depending on the size of the deficiency [Newell et al., 2010].

Apart from self-supply and bilateral contracting, requirements could be met in the Voluntary Capacity Auction (VCA). The VCA was intended as a monthly residual auction to complement the pre-existing self-supply and bilateral trade. It was organized five days before the end of the procurement period. It consequently cleared with little volume and low prices. Having a voluntary residual auction means that, contrary to other systems, the public authority does not intervene to fill a potential capacity gap. On the supply-side, there was a must offer rule and a qualification process for resources: deliverability within MISO was a pre-requisite. Capacity was tested, and the EFORd updated on an annual basis to estimate the corresponding UCAP. Resources were gathered into two categories of "capacity resources": the dispatchable generation (variable and non-variable) and DR. Per analogy to other CRMs, capacity resources were supply-side resources and had an obligation to offer on the day-ahead market (as far as their EFORd allowed them to) and publish availability data (GADs). In turn, "load modifying resources" (behind the meter generation and DR) were regarded as more demand-side: they only responded in case of emergency and were not obliged to offer energy in the market [MISO, 2007].

However, this design was flawed in several ways. Indeed, LSEs had to report their self-estimated peak load, which would only provide the non-coincident system-wide peak load and imperfect adequacy information. The price signal was also imperfect in the absence of locational signal. Those considerations drove the subsequent re-design.

ISO-NE 2010 - to date

According to River Associates [2017], the 1997 capacity market resulted inefficient because congestion was not accounted for: the plants required for SoS reasons remained out of the money. In the absence of locational prices, the price signal miscarried the information on actual scarcity. In addition, capacity price volatility failed to develop an investment-friendly environment. The limits of the ICAP market had been identified as soon as 2000 (see section 1.3.1) and Reliability Agreement were allocated to so-called must-run units to avoid the exit of necessary plants. It had been granted to up to 19% of the system capacity until full enforcement of the forward capacity market (FCM) [FERC, 2010]. In 2006, ISO-NE fixed the level of capacity payment for all resources until the first delivery year of the FCM (2010-2011).

The FCM was implemented in 2008 with a twenty-eight months lead-time planned to regularly increase to reach the final forward period of 40 months as of 2016 [FERC, 2007].

The 2008 auction secured capacity for the delivery year 2010, the transition period with fixed capacity payments lasted between 2006 until the first delivery year of the FCM and ISO-NE witnessed a significant increase in its actual reserve margin during this time⁸⁷ [FERC, 2010]. Contrary to the PJM, the LSEs in the ISO-NE region fully divested their generation. Self-procurement was thus not much of a topic⁸⁸ and the capacity charge is applied to all LSE based on their peak participation in each zone with settlements on a monthly basis [River Associates, 2017]. The capacity⁸⁹ is secured for one year (June to May, monthly payments) through a centralized descending clock auction. Both demand-side and supply-side resources can participate, but new plants and refurbished ones are, however, able to benefit from a contract up to seven years, the clearing price being indexed on inflation. At most, resources can offer their qualified capacity (based on their summer capability) [FERC, 2007]⁹⁰.

As for the demand, the sloped demand curve for the forward capacity auction (FCA) results of the interpolation of four key points that aims at securing enough capacity to meet the 0.1 loss of load expectation (LOLE) reliability target⁹¹. The system operator has to publish the key demand parameters before the auction: net CONE⁹² (price adjustment) and reliability objectives (quantity adjustments). To account for the geographical specific scarcity, a specific demand curve with specific clearing is set up in constrained areas⁹³.

In addition to the FCA, three reconfiguration auctions are organized: one each year between the FCA and the delivery year. They are complemented by three bilateral trading periods. Indeed, the *capacity supply obligation* (CSO) obtained when selling capacity can be transferred in the bilateral market [FERC, 2010]. Units committed into a CSO are required to bid into the day-ahead and real-time markets and follow dispatch instruction: if unavailable at capacity shortage, a unit would see its payments reduced. In addition, the CSO works as a call option in the sense that the payment is reduced of the energy rent at scarcity (when the energy price is higher than the marginal cost of a peaking unit)⁹⁴.

In terms of market power mitigation, a temporary price floor has been designed to be acti-

⁸⁷Since the amount of capacity remunerated was not capped.

⁸⁸[Cramton and Stoft, 2006] still discusses self-supply: capacity resources bid into the FCA, and if cleared, they offset the corresponding LSE's obligation.

⁸⁹See https://www.npcc.org/Library/Resource%20Adequacy/NE_2014_Comprehensive_Review_of_Resource_Adequacy%20-%20RCC%20Approved.pdf accessed on June 7th, 2019 for a description of deratings.

⁹⁰Resources are notified their qualified capacity a year before the FCA. The decision can be challenged in a limited timeframe.

⁹¹The demand curve was actually vertical until FCA 9 (DY 2018-2019) for which FERC approved the system-wide downward sloping curve, and soon after the zonal ones [FERC, 2016].

⁹²Cost of new entry.

⁹³"The amount of capacity needed system-wide in an FCA is termed the net Installed Capacity Requirement (net ICR),⁶ and the amount of capacity needed within a given Capacity Zone is termed the Local Sourcing Requirement for that zone." [FERC, 2014]. See also ISO-NE description of the FCM <https://www.iso-ne.com/markets-operations/markets/forward-capacity-market/fcm-participation-guide/about-the-fcm-and-its-auctions> accessed on May 21st, 2019.

⁹⁴See ISO-NE May 7, 2008 presentation to FERC <https://www.ferc.gov/CalendarFiles/20080507071913-LaPlante,%20ISO-New%20England.pdf> accessed on May 21st, 2019 and [River Associates, 2017].

vated under certain circumstances (Capacity Clearing Price Collar) in to prevent strategic behavior aiming at depressing prices and prevent entry in the FCA. It was replaced by the Minimum Offer Price rule as of FCA 8 (DY 2017-2018). As a matter of fact, the auction has mostly cleared at the price floor during the first decade. Prices have been rising in the last auctions [River Associates, 2017].

While the mix has been evolving towards a lower carbon content, new issues have appeared. The increasing share of natural gas is expected to keep on increasing with the exit of coal and oil plants. This gas dependency raises questions on the fuel security of the gas plants within ISO-NE footprint given the limited pipeline capacities⁹⁵. In addition, concerns about performance incentives have emerged in the past years with increasing plant outage rates due to reduced maintenance investments, limited on-site stocks of fuel⁹⁶, a lower number of gas-fired generators with dual fuel capabilities⁹⁷. In 2015, the first FCA with improved performance incentives was held for DY 2018-2019. The *Pay for Performance* (PFP) are two-sided penalties that are triggered at scarcity, non performing units can be charged as much as \$5455/MWh⁹⁸ while over-performing units can benefit from an extra remuneration up to the same amount⁹⁹. The PFP changes the nature of the incentives: while the peak energy rent used to come as a reduction of the capacity cost burden, the PFP settlement redistributes amongst capacity resources in the way a balancing market would.

1.3.3 The 2010s: Convergence and new challenges

The core of CRM design (for conventional generation) has been stabilized through the two first decades of implementation with satisfying contract duration, deratings and, to a lower extent, performance incentives. Besides, concerns on availability at peak still foster regulatory innovation. Indeed, ISO-NE faces limits on its gas pipeline capacity and the PJM has experienced blackouts in 2013-2014 partly because of inadequate fuel supply. The latter is, in addition, trying to tackle the pricing distortions generated by otherwise subsidized units.

What is striking is the unsettled trade-off between an accurate price signal (considered as the best incentive) that requires a part of uncertainty and revenue stabilization to foster investment. Indeed, the first wave of capacity market focused on the price signal and resulted in rather short-term mechanisms. Price volatility associated with separate flaws

⁹⁵There is an actual debate on the priority of usage on existing gas pipeline capacity and the funding of additional capacity: should gas or electricity SoS prevail?

⁹⁶Transitionally solved with the Winter Reliability Program for DY 2015-2016 to 2017-2018 <https://www.iso-ne.com/markets-operations/markets/winter-program-payment-rate> accessed on October 8th 2019.

⁹⁷See https://www.iso-ne.com/static-assets/documents/2019/04/a00_iso_discussion_paper_energy_security_improvements.pdf accessed on June 7th, 2019 for a thorough discussion of energy security problems in ISO-NE.

⁹⁸The charge is actually gradually phased in to reach this amount as of DY 2024-2025.

⁹⁹See https://www.iso-ne.com/committees/comm_wkgrps/strategic_planning_discussion/materials/fcm_performance_white_paper.pdf accessed on October 8th, 2019.

in the design drove policymakers towards hybrid design both price and quantity based, mainly forward. The indexation of deratings on past unit performance in the PJM is in an interesting way to incentivize performance (to maximize future revenues) while ensuring revenue stability (the revenue is known *ex ante*). However, this type of incentive seems too weak when dealing with extreme and rare events. A unit failure to perform in a given scarcity period will easily average out with the three-year availability average used in the PJM. The 2014 blackout in the Northeastern region of the US led to a recent turn towards capacity performance or pay for performance as it is implemented in ISO-NE and PJM. It is a step further into the hybridization of CRM regulation: the definition of "no excuses" penalties bridges the gap that had kept reliability options apart in the taxonomy. Where reliability options use a financial tool (strike price) to trigger the obligation, recent markets implement more and more technical tools to do so. For instance, France's scarcity conditions are triggered based on demand forecast while the UK and the PJM rather used the system operator physical intervention as an emergency indicator. In this, the tools might be slightly different (physical or financial), the penalties might be calibrated in distinct ways, but the rationale remains the same: making sure that long-term SoS (the existence of capacity) translates into short-term reliability (reduced shortages). In this framework, performance is required to occur when needed, and non-performance can bear no excuses.

With an obvious inspiration from the other side of the Atlantic ocean, the UK CRM design also accounts for its European specifics: the unique transmission grid operator allows for additional centralization. Trying to abstract from the difficulties of integrating non-conventional technologies, but also from cross-subsidy problems, the electricity market reform (EMR) seeks to tackle the energy trilemma all at once: renewables and nuclear are procured through tenders and prevented from participating into the capacity market for already being subsidized. However, battery storage integration in the UK has highlighted the need for additional reflection around non-conventional technologies. With this respect, France tailored capacity products flexible enough to meet the capabilities of demand response and storage. While the trend towards market-based mechanisms is growing, alternative market organizations emerge again: France has implemented a decentralized market in anticipation of the growing role of the demand-side.

The capacity products, which had reached some stability over the different designs (forward-looking centrally procured market with a sloped demand curve, *ex ante* clearing, and high penalties linked to actual scarcity), are also gaining in diversity again with the increasing interest for reliability options (Ireland and forthcoming Italy). Recent evolutions illustrate how non-conventional technologies act as an exogenous shock. Their integration might require a shift in high-level design at a moment where historical CRMs had found some stability.

The debate on non-conventional technologies integration should find additional elements in the coming years given the situation in the PJM and the UK: the status of the ca-

capacity market is currently pending to questions around the advantage provided to some technologies over others (see the discussion in section 1.2.3), either through subsidies or administrative barriers to entry. In this sense, the toolbox that had narrowed thanks to the learning effect starts growing again. The increasing participation of new technologies questions the dominance of identified features. In any case, further learning should soon allow for a new convergence.

Colombia 2012 - to date

The *Cargo por Capacidad* in force between 1997 and 2006 was not strategy-proof because the payment did not come with obligations: the SoS participation of plants was estimated *ex ante* with limited accounting of performance. The resulting shortages led to a necessary redesign: a better definition of the SoS obligations as well as the reliable capacity concept (deratings) [Frontier Economics, 2017]. Although the desire for a market-based mechanism was clear, defining the product resulted in numerous discussions before settling for an energy product rather than a pure capacity one. Consequently, the *cargo por capacidad* was replaced in 2006 by a *cargo por confiabilidad* (reliability charge). As often, bridging between a short-term mechanism and a forward one requires a transition period that, in the case of Colombia, lasted until 2012 under regulated prices: the first auction took place in 2008 for a delivery in 2012-2013 [Ethier, 2014]. It creates *obligaciones de energía firme* (OEF - firm energy obligation), which are financial products with physical back up designed to ensure the SoS: the reliability options. Per construction, those obligations work as a call option: they are triggered when the electricity price reaches a pre-defined strike price¹⁰⁰. The strike price acts as a scarcity indicator. Then, the contracted generators are committed to produce and sell at the wholesale price, the difference between the market price and the strike price is to be paid to the regulator. In fact, this works as a penalty since the obliged unit is bound to produce or buy the equivalent production on the wholesale and additionally pay the price differential every time the wholesale price is above the strike price. In this sense, a unit that would not have been cleared at that moment would already be penalized. The option price is paid independently of scarcity conditions: in a wet year, the option might not be activated, and yet, the contracted plant receives the full option price. In return, it caps their revenues in times of scarcity as they have to give back part of the scarcity rent. This way, consumers are hedged against extreme prices as well. Any production above the committed firm energy can be remunerated at the actual market price. It follows an implicit incentive to produce in scarcity conditions.

The EOFs are procured through centralized descending clock auctions. The market is three years ahead and for one year delivery periods for existing units. New resources which construction was not initiated at the auction time can commit for 1 to 20 years locking in price adjusted for inflation while already ongoing projects (not yet in operation) can commit for 1 to 10 years only. The generator has to produce (at least) the daily

¹⁰⁰See the website of the Colombian Regulator for further information http://www.creg.gov.co/cxc/secciones/obligacion_energia_firme/obligacion_energia_firme.htm accessed on November 15th, 2018.

quantity associated with its obligation when the wholesale price is higher than the strike price¹⁰¹ [Ethier, 2014]. This also means having an adequate fuel supply and transmission capacity to be able to comply (eligibility condition). Generators are also required to declare their technical information so the regulator is capable of estimating their firm energy. To value capacity in terms of EOFs, the yearly production of each plant in scarcity condition (drought) is estimated. This gives an obvious advantage to thermal generators over hydro plants as they are much less weather dependent.

In case a generator foresees an inability to comply, it can procure firm energy on the secondary market or agree with retailers towards load shedding¹⁰². When, on the contrary, the procured capacity three years in advance do not seem enough anymore, reconfiguration auctions are organized to either buy (in case of deficit) or sell (in case of excess) firm energy. In line with technical evolution, changes include unconventional renewables and demand-side integration to the OEF.

As often, design flaws appear in scarcity conditions. In the case of Colombia, this is during *El Niño* phenomenon. Mainly, Frontier Economics [2017] argues that the rapidity and appropriateness of regulatory responses suggest that most flaws were identified beforehand but could not be tackled due to regulatory rigidity. Indeed, the over-commitment of the gas pipeline was known at least since 2003, yet, fuel supply and transport to the thermal plants were the main problems during *El Niño* 2009-2010. This was partially solved through the reduction of gas exports towards Venezuela, but numerous plants also had to switch to liquid fuel. To solve this issue for the longer-term, stricter participation constraints in terms of fuel supply were defined for the future. Since then, securing fuel supply has been a recurrent discussion amongst regulators (see the discussions in ISO-NE (2010) and PJM (2007)). In addition, the reservoir levels and prices did not present a high correlation, which was interpreted by the authorities as potential market power expression [Frontier Economics, 2017]. Although EOFs were not procured through auctions as of 2009, the *Cargo por Capacidad* was already phased out to the benefit of the *Cargo por confiabilidad*.

With respect to the last *El Niño* episode (2015-2016), it is the strike price itself that has been pointed out as a problem. Although the methodology sought to reflect the costs of the least efficient plant in the market, it ended up structurally below the actual production costs of the most expensive units [Frontier Economics, 2017]. According to [Ospina Riaño and Mosquera Palacios, 2016], a mix of factors linked to the international situation further affected the situation. Mainly, the international fuel price used as a reference to the strike price¹⁰³ decreased over the period, but national fuel prices generally remained high over

¹⁰¹This, of course, valid, if the plant is part of the least-cost dispatch.

¹⁰²The demand reduction is discounted from the generator's obligation.

¹⁰³The reference fuel is Platts US Gulf Coast Residual Fuel Oil No.6 1 % sulfur. See also <http://apolo.creg.gov.co/Publicac.nsf/52188526a7290f8505256eee0072eba7/8e7d5ef7bd314e4e0525803e0078de58/\protect\T1\textdollarFILE/Circular065-2016%20Anexo.pdf> accessed on June 10th, 2019 for a discussion on the strike price.

the period due to the closure of the frontier with Venezuela (reduction of imports and increase of transport costs). Further altering the merit order compared to the one used as a reference for the strike price, gas shortages lead generators to switch from gas towards diesel. Such events led the regulator to change the strike price methodology upward (retroactively) and temporarily soften the conditions to take part in the market, facilitate imports of energy (increase gas production) and limit the daily production of reservoirs in times of scarcity. Questioning the design in more general terms, McRae and Wolak [2019] suggests harmful interactions with the forward market.

MISO 2012 - to date

In 2012, MISO aimed at changing its model for resource adequacy in order to improve the price signal and better incorporate load-modifying resources, including energy efficiency resources. In addition, basing the requirements on non-coincident peak load was distorting the adequacy signal by not appropriately considering the positive effect of load patterns diversity. In the new design, the coincident peak load drives the requirements. Besides, nine local resource zones are created to account for capacity and transmission needs [River Associates, 2017]. Indeed, with the integration of the southern regions in 2013, using a copper-plate assumption seems out-of-date in terms of best practices.

On the demand-side, LSEs' annual requirements are still self-estimated. LSEs still provide their coincident peak load, which is used to calculate both the planning reserve margin (%) and the local clearing requirements. The locational component sets the minimum amounts of capacity to be procured locally. They can procure capacity (Planning Resources Credits) through self-supply, bilateral contract, or the annual planning resource auction (PRA - implemented in 2013) that is organized two months ahead of the delivery period (June-May) [Potomac Economics, 2016]. As previously, the PRA is designed as a (voluntary) residual auction. However, the procurement is then centralized with a vertical demand curve. Indeed, contracts must be submitted three weeks before the auction, which procures the residual. Any deviation from their requirements is sanctioned by a deficiency charge. In more simple terms, the retail competition states tend to use the PRA with central procurement to comply with their obligation, which is not the case for non-retail competition states.

On the supply-side, energy efficiency completes the existing panel of planning resources: capacity resources (variable, non-variable generation, internal as well as external resources and DR) and load modifying resources (behind the meter generation and DR). They all benefit from separate qualification processes that, in the end, grant them certificates: "Zonal Resource Credit" (ZRC). The ZRC are standardized products that account for firm capacity as well as location. The unforced capacity of dispatchable units is determined thanks to the effective outage rate (EFORd)¹⁰⁴[MISO, 2017]. The EFORd of dispatchable units is assessed each year based on historical data. Similarly, firm capacity is estimated

¹⁰⁴They actually use a slightly different metric that excludes events out of management control.

based on historical performance. Capacity resources have to be able to deliver capacity within and publish relevant data (GADS). Their contractual obligation regards energy offers on the day-ahead market or the ancillary services. In case of non-compliance, the penalty is proportional to real-time prices (plus uplift) [Charles River Associates, 2017].

UK 2017 - to date

At the time of considering a CRM, the UK was characterized by little interconnected capacity due to its insularity combined with considerable plant retirements [Hancher et al., 2015]. Mainly, aging coal plants were struggling to recover their costs while the pressing environmental regulation was pushing them out. Arguing that electricity markets are characterized by market imperfections¹⁰⁵, the 2010 consultation about the Electricity Market Reform thus proposes a strategic reserve to curb the declining reserve margin [DECC, 2010]. On this targeted option, stakeholders expressed concerns and suggested a market-wide option instead, insisting on the role of DR, storage, and interconnections [DECC, 2011] leading to further consultations¹⁰⁶.

The UK capacity market was finally announced in 2013 with the first auction held in 2014 for delivery year 2018-2019¹⁰⁷. It is thus a four-year-ahead mechanism with central procurement through auctioning, which is financed by LSEs proportionally to their share of the peak load. All non-otherwise subsidized capacity (more than 2MW), including interconnectors¹⁰⁸, storage and demand-side resources, bid into the capacity market as long as they can prove their grid connection and fuel supply¹⁰⁹. If participation is voluntary, conventional generators must either pre-qualify or opt-out from the mechanism. In addition, the market rules identify two types of bidders: the price-makers (DR and new entrant mainly) who can bid up to the price cap, and price takers (existing capacity mainly) who are capped in their bid at half the net CONE. This is explicitly oriented towards market power mitigation. Deratings to be applied to each technology class¹¹⁰ are published along with the auction parameters: the net CONE¹¹¹ and the target capacity¹¹² are estimated by the ministry along with the price cap and the maximum and minimum capacity to

¹⁰⁵According to a white paper of the ministry [DECC, 2011]: (i) "Reliability is a Public good", (ii) "there are barriers to entry in the wholesale market", (iii) "prices in the electricity market may not send the correct signals" (missing money).

¹⁰⁶see [Hancher et al., 2015] for an in-depth discussion of the 2010-2014 process.

¹⁰⁷However, yearly auctions were organized in 2016 for the delivery year 2017-2018 to prevent plant closure, the fifteen-year agreement for new built was unavailable.

¹⁰⁸Interconnectors were actually not allowed to bid into the first auction, but further regulatory evolution was planned to include them.

¹⁰⁹This usually excludes renewable resources that are auctioned in a subsidy scheme and nuclear under CfD (amongst other).

¹¹⁰Average availability over the past 7 winters.

¹¹¹The net CONE of the first auction was based on a Combined Cycle Gas Turbine (CCGT: 49£ /kW) instead of an open cycle gas turbine (OCGT: 29£ /kW) that was initially considered but unlikely to come online in time [Hancher et al., 2015].

¹¹²The capacity target is statistically derived from the loss of load expectation: $LOLE = \frac{Net\ CONE}{V_{oLL}}$ see [DECC, 2013].

be procured. The sloped demand curve is derived from those parameters [DECC, 2014a]. The cleared capacity secures capacity remuneration for a year, refurbished units, and new plants can see this period extended up to respectively 3 and 15 years. In exchange for the remuneration, the cleared units are bound to deliver energy when a "Capacity Market Warning" is issued (at least 4 hours ahead), they also have to prove availability during system stress events¹¹³ and comply with any verification mean in place [DECC, 2014b]. Demand-side resources limit their commitment to the time banded obligation, which restricts the obligation to specific periods of the day; they then only receive 70% of the capacity price [National Grid, 2015]. Any failure to comply exposes to penalties that depend on the auction clearing price.

To ease the capacity target correction, an adjustment auction with a one-year lead-time (T-1) is scheduled in addition to the main auction (T-4). It is also more suited for DR and storage: some capacity is always held back from the T-4 auction to be procured in the T-1 for this purpose¹¹⁴. Following the T-1 auction, capacity obligations become tradable on secondary markets so generators can adjust their commitments. Such a risk is born by the end consumers from whom the capacity charge is collected on a monthly basis based on their contribution to peak demand (share).

The interesting characteristic of the UK capacity market is that it has been implemented in compliance with other energy policy objectives as part of the Energy Market Reform. Contracts for differences and feed-in tariffs were designed to be complementary so renewables can be excluded from the capacity market and only accounted for in the reliability target in a passive way. This is a smart way to avoid the everlasting discussion on actual reliability of intermittent technologies as well as possible strategic bidding from subsidized resources¹¹⁵. Although this approach allows for much simpler rules, it has shown its limits with the recent ruling from the European Court of Justice that considers the UK design might create disproportional discrimination against clean energy projects since the commission did not initiate a formal investigation procedure when granting its approval [European Court of Justice, 2018]. The argument lies in the fact that proving eligibility and reliability verification is more demanding for demand-side resources than for thermal generation.

France 2017 - to date

The liberalization process initiated by the European Commission created a debate on the role of the incumbent (EDF) on the market. The ownership of nuclear power stations

¹¹³Settlement period during which the system operator activates demand control (either demand reduction instruction issued or demand disconnection takes place) for at least 15 continuous minutes.

¹¹⁴This is in a similar fashion as in the PJM's RPM: as of DY 2012-2013, the PJM removed a short-term DR product (interruptible load for reliability that committed just before the beginning of the delivery year, without auctions and at the BRA's price) but reduced the demand in the BRA to allow for additional DR procurement in the incremental auctions.

¹¹⁵Problem currently faced by the PJM that struggles to agree with the FERC on the best capacity market rules.

and hydro-power plants established a form of dominance on the market that had to be accounted for. The unbundling of transmission, retail, and generation had also left the TSO (RTE) with the SoS responsibility without dedicated means to do so. In parallel, due to high-temperature sensitivity, the peak demand kept on growing at a pace of 3% per year, while total demand only grows by 0.6% annually on average [RTE, 2014]. Those three characteristics of the French system (Nuclear power, Hydropower and steep load duration curve) are inherited from the post-war period where the fear of dependence to energy imports (mainly gas and petroleum) lead to over-investment in nuclear capacity (cheap baseload) as well as great incentives for power consumption: mainly, electric heating was developed to absorb the surplus.

In 2005, plant operators started alerting the French authorities on their lack of profitability and contingent weak investment incentives. A situation that officially appeared in the multiyear investment plan for the 2009-2020 period published in 2009. It was directly followed by the creation of a working group on SoS, which, a few months later, advised for capacity obligations with a certificate market [Hancher et al., 2015] with first delivery year in 2015¹¹⁶. In 2010, the NOME¹¹⁷ law is issued in line with the report's recommendations: one of the five objectives of the law was to reinforce SoS through direct or indirect capacity (or load management resources) procurement by retailers so to ensure continuous supply for its clients [Marty and Reverdy, 2017]. In 2012, RTE is mandated to draft the capacity market's technical rules and engages in consultations. In 2014, the draft rules of the French capacity market were issued [RTE, 2014], yet to be approved by the regulator, the ministry, and the European Commission. The latter finally gave its conditional approval in 2016, so auctions could be carried out in 2016 for the delivery year 2017. Due to the reserves expressed regarding competition, investment in new capacity and cross border participation as well as the delays in implementation, the final design is not fully effective et but the market is already in place¹¹⁸. Consequently, the description below is only partially representative since the design is expected to evolve until 2021 [RTE, 2017].

It aims for a 4-year forward decentralized mechanism of capacity obligations. Each retailer has to cover its normalized peak demand with the corresponding amount of capacity certificates. Per design, there is competition on the two sides of the market. The mechanism defines the obliged parties as being any consumer of electricity. This includes not only the LSEs, but also the network operators (TSO and DSOs) for their losses. Their obligation is evaluated *ex post* based on their realized peak demand calibrated thanks to the market parameters published by RTE 4 years in advance. Those account for the target reserve

¹¹⁶Refer to the so-called Sido-Poignant report after the names of the co-chairs of the working group, respectively from the high and low chambers. Available at: <https://www.ladocumentationfrancaise.fr/var/storage/rapports-publics/104000160.pdf> accessed on May 3rd, 2019 and [RTE, 2012] that identified a potential capacity gap as soon as 2016.

¹¹⁷*Nouvelle Organisation des Marchés de l'Electricité* available at <https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000023174854&categorieLien=id> accessed on May 3rd 2019.

¹¹⁸For instance, the forward period is still limited to 1 year in terms of auctions while the objective is to reach 4-years ahead.

margin as well as a weather correction, which normalizes their observed consumption on peak hours to the actual need for capacity. With the decentralized approach, the demand is naturally elastic through changes in the expectations and opportunity costs of market participants.

On the supply-side, installed capacity has to get certified. The level of derating for each unit is self-defined (within a credible range), actual contribution at scarcity is to be measured *ex post*. The obligation to be available runs from January to March and then from November to December. It is limited to 15 critical days (PP1). In addition, certification control can occur anytime during up to 25 critical days (PP2 that include the PP1)¹¹⁹. Critical days are announced the previous day based on expected demand. Any deviation is penalized proportionally to the reference capacity price so the cost of the option is, at any time, higher than the cost of procurement. The *ex post* valuation of participants' compliance guarantees a form of fairness: efforts to mitigate peak demand are explicitly priced as well as the availability at peak. The counterpart for this is the need for continuous adjustment of expectations: bilateral trading can occur at any time before, during and after the delivery year while auctions are organized one or several times a year between the beginning of the process (4 years in advance) to the end (one year after delivery). Due to the concentration in the French market, market power mitigation has been carefully assessed by the European Commission: the three main integrated actors have specific transparency requirements. For instance, their transactions have to be reported to the regulator in detail. They also face stricter constraints on certification and sale offers through the so-called "certification tunnel"[RTE, 2017].

Most of the existing thermal capacity is bound to get certified four years before the delivery year, so a majority of supply is identified in advance. However, demand-side resources have until two months before the beginning of the commitment period to get certified, so their availability is as sure as possible. DR can actually choose to bid either as demand-side (reduction of capacity obligation) or on the supply-side (certified capacity). *De facto*, most demand resources prefer getting certified to benefit from a reduced obligation¹²⁰. New capacities are to be granted a seven-year contract, but exact conditions of procurement are to be clarified. In addition, otherwise subsidized capacity and existing capacity products such as the ARENH¹²¹ are excluded from the market, while cross border participation should be granted explicit valuation in the coming years.

Arguments in favor of decentralization include a more accurate capacity procurement [Woodhouse, 2016] but also better liability of market actors to their contribution to SoS: demand response can be valued both on the demand and supply-side. This contribution

¹¹⁹Control can lead to uneconomical activation and is thus limited to critical days as well.

¹²⁰When qualified as demand reduction, resources have to reduce their demand during scarcity hours, a maximum of 15 days a year. On the supply-side, they have to reduce demand based on a price signal, which might occur less often.

¹²¹*Accès Régulé à l'Électricité Nucléaire Historique*: regulated access to nuclear energy that allows all retailers to benefit from the low-cost electricity produced by the amortized nuclear plants.

to the worldwide regulatory framework would be limited without the innovative definition of the deratings that ensure standard certificates. Indeed, the deratings account not only for the average availability at scarcity, but also for the duration of availability¹²². In a context where the need for flexibility and for long-term SoS are often opposed, this clearly defines the objective of the CRM as a tool to meet the peak demand. In a country where the peak demand is driven temperatures, peak shaving appears as a suitable option. In addition, the decentralized and continuous aspect of the mechanism raises questions of inter-temporal arbitrage. Amongst other measures, the implementation of an asymmetric penalty for rebalancing¹²³, as well as a minimum offer rule for the biggest generators, limit the strategies in quantities.

Ireland 2018 - to date

As of October 2018, a significant change in the Irish market is introduced with the implementation of the Integrated Single Electricity Market (I-SEM) as part of the European market integration. The I-SEM raises the price cap to the estimated VoLL (approx 11 000€/MWh [European Commission, 2017]). The new design also changed the capacity mechanism, reliability options with a strike price have been auctioned in 2017 for the delivery year 2018-2019 (the beginning of the I-SEM operations). Under the obligation to justify such a mechanism to the DG competition in charge of state aid, the committee (SEMC) has evoked the public good characteristics of the SoS that characterizes missing money. Besides, increasing renewable generation combined with limited interconnections and demand response in a relatively small market make it difficult for investors to assess their future profitability accurately. Indeed, any flexible unit is likely to be big enough compared to the overall market size to significantly impact the revenue stream.

This new market-based CRM is a significant change compared to the previous design. It also presents an evolution in line with the international trends. The central procurement of reliability options is performed by the market operator (SEMO). Designed with a four-year lead-time similarly to the British capacity market, it, however, includes a transition period: all the delivery years before 2022-2023 will only be auctioned once, with one-year lead-time. Then, auctions will be organized both four years, and one year in advance (adjustment auction), additional auctions might be scheduled if needed. In addition, secondary trading is allowed in case qualified units would need to adjust or cancel their obligation [SEM, 2019].

The product traded is derated capacity that accounts for the statistical contribution to the SoS [Single Electricity Market Committee, 2018]. Derating curves are calculated

¹²²Indeed, a thermal plant can produce without discontinuity, but a demand-side resource or storage are more constraint on the length of their contribution. To ease the estimation of the derating, RTE provides a (concave) conversion function that accounts for the number of consecutive hours, as well as the number of successive days a unit can be activated. The product of the two coefficients gives the actual derating.

¹²³The penalty is function of the reference price of capacity, but the reward for positive deviations is capped, and the penalty for negative deviations of more than 1 GW is increased.

by the system operator and differentiated based on technology and unit size. They also account for the duration (the consecutive hours the unit can provide SoS) when considering storage. The successful capacity providers receive the clearing price for their option sale. In return, they have to pay back the market price differential every time the wholesale price exceeds the administrative strike price as defined in the option¹²⁴. Both existing and planned units can apply for qualification, which is mandatory for existing dispatchable units and interconnectors. It follows that capacity units are required to be within the SEM footprint. Existing units only secure the payment for a year, while new capacities can apply for up to ten-year contracts (subject to a termination fee so to ensure the plant is actually built). The option comes with the obligation to deliver energy by entering into contracts in the day-ahead market, the intraday market, and the balancing market.

Based on an eight-hour LOLE objective, the SEMC defines a capacity target and builds a downward sloping curve. The legally defined method is flexible in the sense that the system operator is required to define at least two points (price and quantity) and at most ten of them to be interpolated in order to build the demand curve. The resulting demand curve will be published with the other auction parameters in the final auction information pack. The mechanism is funded by the capacity charge raised on the electricity suppliers¹²⁵ (LSEs) in the proportion of their peak demand. The strike price acts as a hedging instrument for suppliers: it effectively caps the cost of electricity as a compensation for the capacity component. Because of the differential payments, the net cost of the mechanism is only known *ex post*. In addition, market power is limited on the capacity market by capping the bids of existing units to a portion of the net CONE. Demand-side and new capacities are subject to a higher price cap (1.5 Net CONE) [Cornwall Insight, 2018].

The Irish mechanism presents several difficulties. The first one lies in the auction clearing of bids that can be either flexible (bids can be partially changed) or inflexible. Besides, a constrained auction has been designed to secure units "out of merit" in constrained areas. The reliability option closely links energy and capacity products, which raises concerns about the integration of the demand-side units. Indeed, their compliance with the option contract lies in demand reduction: they do not produce and, as such, do not receive the wholesale price. The reimbursement of the wholesale price differential only applies when the unit is not compliant. Due to their short-term nature, part of the capacity procurement is withheld from the T-4 auction so that demand-side units can clear in the T-1 auction. They also benefit from the same deratings as the storage units, given that their demand reduction cannot be activated more than 6 hours in a row.

All in all, the different CRMs display signs of cross-system learning and the nature of the regulatory innovations suggests three different learning periods. Such empirical evidence of learning and the regulatory consequences are analyzed in the following section.

¹²⁴Liability is, however, capped to 1.5 option price.

¹²⁵The Republic of Ireland and the UK share the responsibility of the charge based on their share of end-user consumption.

| | | Experiments (1990s) | Improvements and further impl. (2000s) | Convergence and new challenges (2010s) |
|----------|--|---|--|---|
| UK | Exo. factors Motives Lessons | Insularity, natural resources (gas and coal) Demand growth Strategic behavior, capacity withholding, volatility | | EMR and coal plants retirement SoS capabilities of new tech., role of decentralized generation |
| Spain | Exo. factors Motives Lessons | Peninsula, hydro power Unbundling and stranded assets Sensitivity of performance parameter setting: Peaking plants running at loss | Reduce cost of SoS Role of parameters settings resulting margin and financial burden | ⇒ No major reform |
| Colombia | Exo. factors Motives Lessons | Hydro power, el Niño, political instability Blackouts and market risk reduction Shortages (no obligations). Need for obligations and deratings, suspicion of market power | ⇒ No major reform (market power mitigation for both thermal and reservoirs) | Implement obligations, deratings and market prices Fuel supply problems, Shortages due to strike price level |
| ISO-NE | Exo. factors Motives Lessons | Nuclear Historical institutions poor price signal (locational constraints) | Implement locational prices Market power mitigation | ⇒ No major reform |
| NY-ISO | Exo. factors Motives Lessons | Heterogeneity of the regions Historical institutions Adjustments in regulation (no full redesign) | ⇒ No major reform | ⇒ No major reform |
| PJM | Exo. factors Motives Lessons | Densely populated NYC and Long Island Historical institutions Market power, poor price signal (missing money, locational constraints, volatility), inefficient ICAP | Implement forward CM and locational constraints New technologies, market power mitigation | Market power mitigation (subsidies) Blackouts 2013-14 (fuel supply), subsidies distort the market |
| MISO | Exo. factors Motives Lessons | | High share of vertically integrated utilities Poor price signal: coincident peak load, congestion | Improve price signal |
| Italy | Exo. factors Motives Lessons | | Bottlenecks and dependance on imports Blackout 2003 (transitional) | Blackout 2003 (Final), profitability gap |
| Ireland | Exo. factors Motives Lessons | | Insularity, capacity gap, small market compared to plant size, increasing RES Low reserve margin, absence of scarcity pricing Limited (energy market based on marginal cost) | Electricity market reform (I-SEM) |
| France | Exo. factors Motives Lessons | | | Nuclear, thermo-sensitivity Capacity gap and Electricity market reform |

Table 1.7: Exogenous factors, motives and lessons

1.4 Analysis

The intuition behind social learning is that beliefs naturally converge after a certain amount of time. We argue that this happens in regulation (CRMs) when features do prove to work efficiently. However, substantial heterogeneity between systems acts as a vector of divergence, while exogenous shocks tend to slow the convergence process down. Section 1.2 has highlighted the dynamics of policymaking and the channels through which learning occurs. Complementarily, section 1.3 has taken a closer look at ten different systems (SO-NE, NY-ISO, PJM, MISO, Italy, France, the UK, Colombia, Ireland, Spain) and identified both the local specifics and the observed outcomes of policymaking over time. This last section aims at using system-level choices and lessons to corroborate the hypothesis of cross-system learning and to understand the pace of adoption of efficient features.

1.4.1 Empirical evidence of learning

Applying the conceptual framework to a panel of systems highlights the diversity of exogenous factors and motives that can lead to CRM implementation. Motives can be linked to policy objectives and market imperfections. For instance, Ireland’s first electricity market design did not allow for scarcity pricing, leading to an obvious problem of missing money. In Colombia, the time scale of uncertainty induced by its geography is so large that the market imperfection becomes close to self-evident. In Italy, the 2003 blackout was a tipping episode that naturally triggered regulatory measures to avoid future SoS problems. In the eastern US systems, it was the existing institutions that drove implementation. Similarly, numerous systems with limited interconnections (insular, peninsular) have implemented a CRM rather early on compared to their closest neighbors (Ireland, Spain, the UK or even Greece –2005–). The generation mix also plays a role in CRM choice: ten years after the Colombian decision to implement a call option, this alternative seems more and more attractive with Ireland and Italy choosing this design¹²⁶, Belgium is currently considering it. However, a non-negligible difference between the Colombian mechanism compared to other CRMs is that it procures its annual load instead of capacity. If the difference is mainly arithmetic¹²⁷, it reflects the dependence of Colombia to hydro-power: while the hydro capacity is steady over time, its practical capability to generate depends on inflows (hydrology) and dams optimization. In line with the hypotheses of section 1.2.4 and section 1.2.2, exogenous factors, and motives seem to be drivers of divergence between the CRMs implemented.

In addition, previous sections identify the learning channels, be it through *elite networking* (interaction with the same counsellors), *policy communities* (see figure B.2) or *penetration* (lobby) and *harmonization* (supra-system regulation). In practice, the hypothesis of

¹²⁶The Italian options have been validated by the EU but remains to be voted locally.

¹²⁷Dividing the annual load –resp. the annual contribution of a given resource– by the number of hour loops back onto derated capacity.

learning is supported by the synchronized timing –and content– of designs and re-designs. The timing suggests that learning would occur in cycles. Three learning periods emerge from the analysis of the 10 systems. Those periods naturally stand out from the pace of adoption and redesign. As illustrated in figure 1.3, this occurs in clusters. The content of designs implemented carries as much information as to their pace: the main converging features are highlighted in figure 1.3. Indeed, in the 90s, the first CRMs are implemented thanks to the toolbox at hand. It was, at the same time, unconstrained –no features had proven inefficient–, and also limited by the lack of experience on the features actually needed. It resulted in a range of rather simple CRMs. In the 2000s, some learning could be derived from the 90s designs: the range of high-level features considered shrank, while performance incentives and market power became broadly discussed. This allowed the emergence of a somewhat stable design in the 2010s: all new designs are market-based with a forward period and market power mitigation. They claim to be technology-neutral and include comprehensive deratings, strong non-compliance penalties, and detailed verification means.

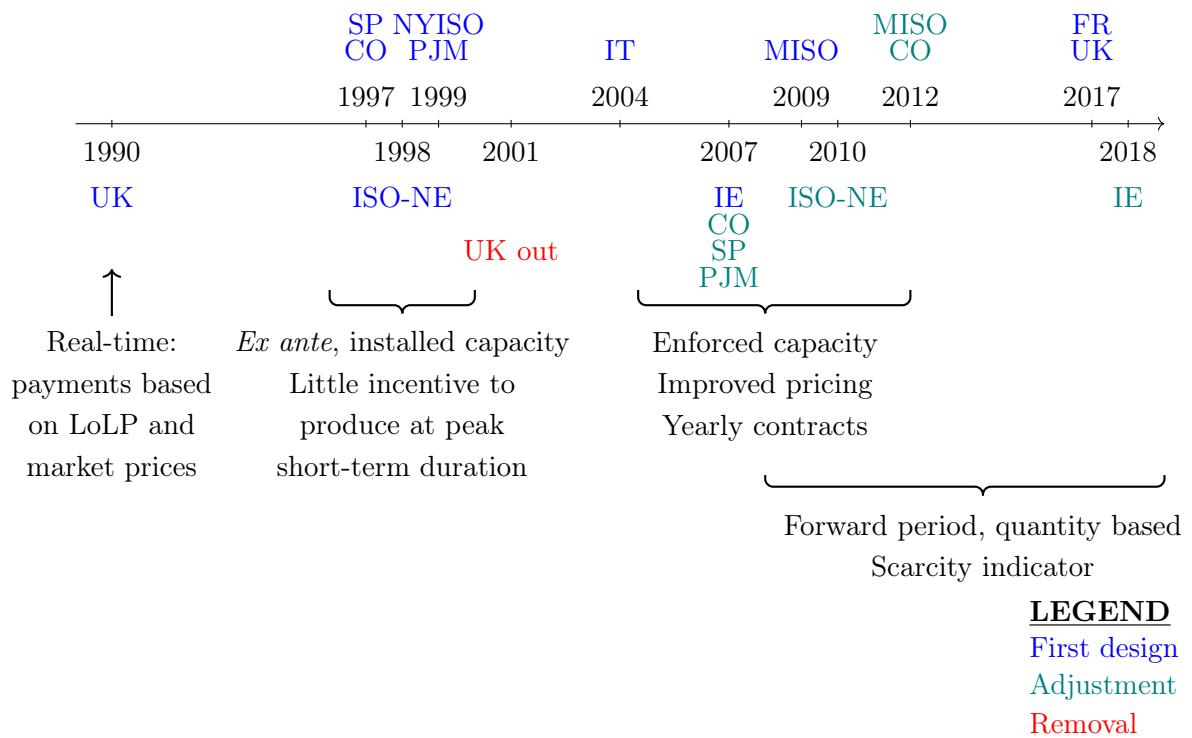


Figure 1.3: Timeline of CRM implementation and redesign

The reduction in design variations further supports the learning and convergence hypothesis. More specifically, high-level features have been quite obviously converging towards market-based mechanisms. However, some implementation features also display signs of learning. When a feature emerges as increasingly included in the regulation, a sound assumption is that it has proven its superiority compared to some other alternatives in the toolbox described in section 1.2.3. For instance, the consensus towards market-based mechanisms has led to increasing considerations about the estimation of the amount of

capacity required for SoS purposes. In turn, this requires a thorough definition of the shape of the demand curve. Similarly, all attempts to set the capacity price either *ex post* (former Irish, Italian, and British schemes) or close to the delivery year (former PJM or ISO-NE markets) have been abandoned for a more stable price signal. The characteristics chosen to obtain such a price are often a rather long delivery period (1 Year and more for investments), an even longer lead-time to foster market entry (construction time). An essential drawback of having a significant lead-time is the reduced precision of the capacity target: expectations might change as the delivery period gets closer. This has fostered the implementation of adjustment auctions (*ex ante* to maintain the *ex ante* clearing). The counterpart of this price stability is a poor correlation with market conditions, which in turn results in weak incentives. The natural consequence of convergence towards *ex ante* clearing has created a common issue to define obligations towards system security (expected resources behavior) to compensate for the reduced accuracy of the price signal. Complementarily, uncovering the efficient penalty that would effectively restore the performance incentive of accurate pricing -without the drawbacks of *ex post* prices- has been a struggle that remains unsettled. In turn, obligations and penalties require the possibility for capacity resources to exchange the former in order to avoid the latter. This all makes much sense from today's perspective, but it has taken some time for designs to converge on those questions. Drawing from this reasoning, I have identified 16 "must-have" features i.e. features that are increasingly consensual in CRM designs (see table 1.8).

1.4.2 An attempt to quantify convergence

Taken all together, the features identified in table 1.8 features represent what can be called a "target design". They are used to rate the designs presented in section 1.3 in terms of compliance with the "target design". Figure 1.4 represents the evolution of the average index in the panel of 10 systems (see table B.1 for the detailed view on each system rating). The upward trend shows clear learning cycles. Both the variance (represented in grey) and the number of CRMs (plain line) reflects the inertia of regulation. This reveals two things. First, CRM implementation comes in clusters, meaning that several systems implement more or less (dis)similar designs based on a shared pool of knowledge. Second, when implemented, a CRM is usually reformed within a decade. This means that a design is tested out to derive lessons before any change is made. Inertia is mainly driven by the time needed to analyze the efficiency of a CRM, the time needed for such information to flow, and the time required by the regulator to make decisions.

Per construction, the earlier designs benefit from a poor rating while the most recent get a perfect mark: this is artificial but rather useful to set out the pace of convergence. Figure 1.4 represents the evolution of the average rating of the contemporaneous CRMs in the panel over time. As expected, it starts rather low since the first learning cycle has mainly focused on high-level features -that are less numerous than the remainder of possible features¹²⁸. Thus, market-based mechanisms have appeared more attractive

¹²⁸As convergence is towards market-based mechanisms, some features are *de facto* irrelevant for other types of

| | Convergence: Indice features | High variance: scattered features |
|--|---|--|
| Type of CRM | Market Volume Centralized | |
| Product | Eligible capacity Derated (production at scarcity) Tradable quantities | Method for derating |
| Contract | Obligation (availability or production) 1 year delivery period 3 year lag period Non compliance penalties (proportional to price) Market power mitigation | Critical period indicator Transparency measures Exit penalties |
| Capacity demand | Demand based on CONE/Missing Money Sloped demand curve | Reliability criteria Verification means |
| Market | <i>Ex ante</i> clearing <i>Ex ante</i> Adjustment auction | Locational <i>Ex post</i> Adjustment auction |
| Contribution from non-conventional technologies | Interconnectors Energy efficiency | Method for deratings DSR Storage |

Table 1.8: Converging features

from the first cycle on, but this does not mean that contemporaneous designs were not perfectible. It seems that new adopters of market-based solutions have waited for the end of the learning period, for lessons to be drawn, before taking the plunge. The solutions proposed to fill the identified gaps have sometimes been similar as with the increasing implementation of forward capacity markets to stabilize revenue streams. It has also been quite different in some other cases, such as restoring the price signal (call options, increased obligations, increased penalties, etc¹²⁹). Ultimately, the nature of the most efficient performance incentives remains under discussion as of now. In any case, the

CRM, leading to a low rating.

¹²⁹Systems have been reluctant to implement all these options at once because of the re-regulation it implies as well as the financial burden it might represent.

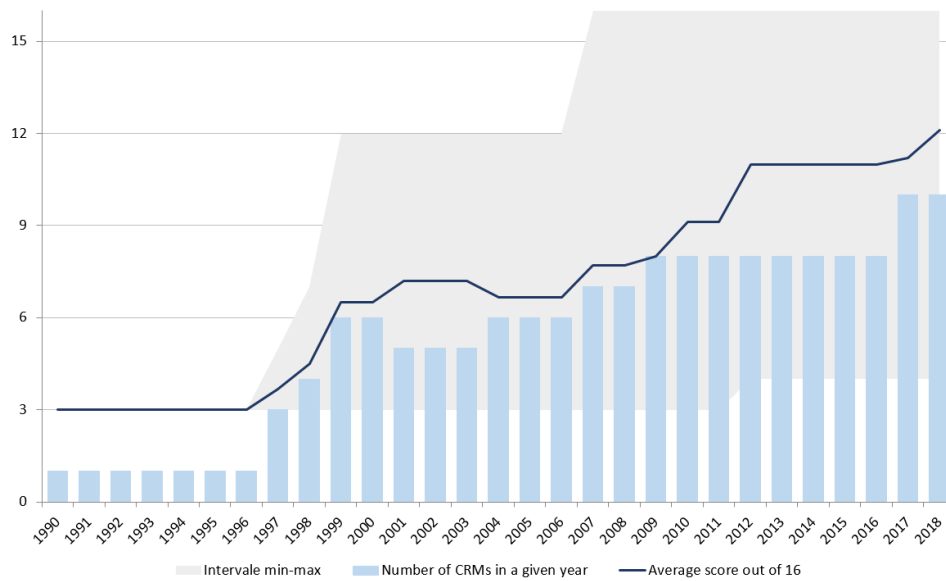


Figure 1.4: Statistics: Indices of target design (10 Systems)

number of features concerned with the fine-tuning of a market-based CRM was much higher than the number of high-level features. There are consequently more significant learning steps in the 2000s than in the 1990s.

Because of the structural heterogeneity between the systems, best practices diffuse unevenly over the different countries. This explains the spread in ratings as illustrated by the grey zone in figure 1.4. Inertia in regulation is another explanatory factor: the systems with the lowest rates are always systems that have delayed the change in their mechanism (compared to the inefficiencies identified). Indeed, the Colombian capacity payments are rated only 3. This is mainly for being payments, but the transition period towards reliability options (2006-2012) also artificially maintains a low indicator. Similarly, the reliability options designed to replace the Italian payments (2004) have only been accepted by the European commission in 2018. As they were drafted to be transitory, they only display 4 of the "target features". Similarly, Spain's payments are on the hedge of European legality¹³⁰ and might be changed as well. As soon as the change is accounted for, the range of rates should lessen: the French design has the lowest rating (10) mainly due to its innovative approach aiming at a better integration of non-conventional technologies (especially DR).

Where high-level design was the first category to converge, it is also the first shaken by the new requirements of non-conventional technologies. Indeed, France chose to move away from central procurement to ease demand response integration while Ireland and Italy neglected a pure capacity product for a reliability product. Once more, it is interesting to notice that geographical proximity seems to synchronize learning. Indeed, the US designs

¹³⁰<http://ieefa.org/ieefa-europe-legal-challenge-spains-capacity-market-payments-well-founded/> Accessed on October 8th, 2019.

evolved in parallel as a consequence for their similar culture and common advisers: their best practices were later on propagated. However, the fact that system boundaries blend into state borders in Europe increases the influence of culture and institutions over a given design. Even though the French and British mechanisms came out simultaneously, their design is quite different. This is clearly because the focus has been set on different elements. The British capacity market excludes otherwise subsidized generation from the market as a way to deal with non-conventional technologies out of the capacity market. On the contrary, France used the existing integration rule for DR¹³¹ as a basis for its design. This might be a nightmare for neophytes, but it actually provides products adapted to non-conventional technologies capabilities.

Although this approach allows to set out the pace of learning, several elements are disregarded, limiting the reach of the analysis. For instance, it is assumed that the regulation is not updated between substantial redesigns, but section 1.3 shows that this is far from empirically verified. Another approximation of this rating methodology is the selected year of implementation: a given design is considered in force as of the first delivery year. The first delivery year (DY) is unequivocal and represents the first economic effects of the measures (this method will be used again in chapter 4). One could, however, argue that decisions have been taken far ahead in time, which could represent the actual turning point in the regulatory process. This is very true but questions what date to consider as regulation-making is an iterative process that often takes several years to fine-tune. Taking the example of ISO-NE, the change towards a forward capacity market was discussed as soon as 2000 [Cramton, 2000], yet, FERC gave partial approval to such a change in 2006 [FERC, 2006a], final approval in 2007 [FERC, 2007] for a delivery year in 2010. All in all, where we try to provide a clear picture in figure 1.4 for the argument, the reality of regulation-making is obviously more complex.

1.5 Conclusion

This chapter has developed a novel framework to analyze the evolution of CRM designs since their inception. It identifies the converging and diverging forces that affect the design of CRMs. Further, it defines a set of useful features to characterize and compare the CRM designs implemented in different periods and places. Applying such a framework to a panel of ten systems over almost three decades, sets out the convergence in design and highlights the existence of learning cycles.

At the system level, the two contradictory forces come at play. On the one hand, the heterogeneity between the systems requires each CRM to be tailored according to the local specifics. Mainly, exogenous factors (section 1.2.1) as well as motives for implementation (section 1.2.2) tend to make each problem and thus each solution (CRM) unique. On the other hand, cross-system learning appears as a strong converging force: combining the lessons from past experiences sets out the features that tend to work as expected

¹³¹ *Notification d'Echanges de Blocs d'Effacement* (NEBEF).

("dominant" features). The regulators will increasingly adopt those (converging features) while the others might either be dropped ("dominated" features), or kept with a high variance in designs (tuned features that match the local context). At the system level, this means that the regulator benefits from both its own and foreign experience, although the latter is not fully instructive due to system heterogeneity: perfect convergence in the sense of "one design suits them all" will never occur, and partial convergence -towards the "dominant" features- is going to take time.

However, this dichotomy between converging and high variance features (as displayed in table 1.8) denotes a static analysis of the situation. Indeed, disruptions, such as technical change, tend to upset the picture because some "dominant" features cease to be adapted in face of the new challenges, creating an increase in the variance of the implemented features. From a static perspective, country-specific and disrupted features would both display a high variance, which makes them difficult to differentiate. The necessity to analyze the possible designs from a dynamic perspective highlights the existence of ongoing disruption. Technical change has made possible decentralization, decarbonization, and digitalization all at once¹³². In this sense, technical change has driven a deeper transformation in market dynamics, and CRMs have tried to adapt to such a change during the last learning phase. The case for new technologies in all its forms is increasingly being tackled, and there are good chances that new converging features with this respect emerge during the next learning phase.

¹³²See <https://www.power-technology.com/features/featuredecarbonisation-decentralisation-and-digitalisation-the-big-drivers-at-powergen-2017-5856615/> accessed on October 8th, 2019.

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Appendices

Appendix A

Case study: Reliable capacity

To make sure the capacity sold is reliable, capacity resources are obliged to provide the equivalent amount of energy in short-term mechanisms. In this design, the derating is natural: an outaged plant can neither sell capacity nor energy. When the market is daily as in PJM between 1999 and 2007, the average capacity sold over the year should equate the perfect derating for the given plant. However, these mechanisms proved to be flawed in two ways [Sioshansi, 2008]: one could withhold capacity –selling energy but not capacity– or the contrary –sell capacity and make uneconomical bids on the day-ahead market. These strategic behavior impaired the investment incentive in all the systems that implemented it. This partially explains the decline of such a feature in new CRM designs as soon as the 2000s: the England and Wales Pool first dropped their mechanisms, followed by New England in 2006 and the PJM in 2007.

The alternatives considered by the regulators have been either to partially or totally disconnect the capacity revenue from the energy revenue¹. The Italian (2004) and the Irish designs (2007) both divide the capacity remuneration into several components being either *ex ante* or *ex post* ones. The *ex ante* components are often based on installed or firm capacity while the *ex post* components are still linked to the actual energy produced as a sound performance incentive. For most of the other new designs, the price is fully decided *ex ante* based on installed capacity derated for the historical performance. The actual achievement would not drive the amount of capacity revenue anymore, but the noncompliance penalty.

In the (1999-2007) framework, the PJM would scale up the peak demand with an average outage rate so the total capacity secured effectively procures the adequate level of reliability. With respect to the *ex ante* price signal, deratings are obviously needed on the supply-side to have an effective price signal. All existing designs do now include differentiated deratings. The methodology to set those deratings, however, dramatically varies from one system to another.

¹Not that the increasing use of reliability options and important energy related obligations, the behaviors on the two markets currently tend to be increasingly linked.

The US Northeastern states auction what they call "unforced capacity" (UCAP). To estimate the UCAP, two underlying concepts are needed. First, the maximum available capacity of a unit at peak ("installed capacity" - ICAP in PJM, "Dependable Maximum Net Capability" - DMNC in NYISO and "Generator Verification Test" - GVTC in MISO) already accounts for the technical availabilities of the different technologies: absence of wind or sun at peak time or lower performances of thermal due to the summer heat. To calculate the UCAP, the ICAP is, in turn, scaled thanks to an Equivalent Demand Forced Outage Rate (EFORD), which accounts for the probability of a given plant to be unavailable when there is demand for this specific unit. In the PJM, MISO, and NYISO, the UCAP is the standardized capacity unit to be auctioned. In MISO, the EFORD is derived from historical performance. In the PJM and NYISO, the unit EFORD is based on one-year outage data² including "outside management control" events such as storms and fuel supply interruption³. When such data is unavailable, class averages are used. In ISO-NE, the ICAP is auctioned directly [River Associates, 2017].

As for Europe, technology wide deratings dominate. In the UK, the derating considers the average availability of each technology class⁴ over the past seven winters. A significant flaw in this design has been using a single derating for all storage technologies (96% for both pumped storage and batteries). To fill this gap, a 2017 ruling announced new deratings that would account for the duration, reducing the contribution of all storages with a duration inferior to 4h (down to around 20% for half-hour batteries depending on the auction)⁵. Similarly, the new Irish mechanism includes deratings per technology. However, they consider derating curves by technology so to include potential variations in availability depending on the size of the unit. Banking on the British experience, storage units' deratings benefit from a third dimension being duration. The French case is a bit peculiar since it allows both the supply and the demand-side to adjust positions after the performance realization. The amount of capacity to be certified is then declarative, but the suppliers bear the cost of their error forecast with respect to their own reliability.

All in all, every system has developed some sort of deratings so only the reliable capacity is paid for. If this feature can be considered as universal, the methods for deratings vary significantly from one system to the other. In Europe, only one factor is usually applied. In the US, the methodology is a two-stage calculation. The differences go beyond methods, the events considered into the final derating factor are disparate. In addition, using technology class averages presents a lower investment incentive compared to a unit-specific derating as it is applied in the US, but it is also less data-intensive. Similarly, the UK uses seven-year averages that are more likely to reflect future performances. Using only the past might be less robust in terms of reliability contribution, but it certainly

²<https://www.aeso.ca/assets/Uploads/Dispatchable-Resource-UCAP-Calc-Comparison.pdf> accessed on August 22nd, 2018.

³In PJM, this changes slightly with the capacity performance recently implemented.

⁴Published with the auction parameters every year.

⁵See <https://www.energy-storage.news/news/major-blow-for-uk-energy-storage-in-capacity-market-following-de-rating-rul> accessed on June 11th, 2019.

gives a stronger incentive to perform. Indeed, underperforming one year would not only lead to a penalty but also reduce the quantity to be auctioned the following year.

Since the 2000s, convergence towards the use of deratings appears in order to remunerate the contributions to the SoS fairly. Regarding the methodology, however, a trade-off between procurement accuracy and performance incentives emerges. This leads to different deratings both in terms of methods and events accounted for: until recently, the two priorities have coexisted without one dominating the other. However, the British and Irish example enlightens on the limits of plain technology deratings for new technologies. The current trend thus seems to discriminate against additional units' characteristics, making derating methodologies converge towards lower standardization. Indeed, storage and demand-side response require unit-specific reliability controls due to their specificities (i.e. being both demand and supply-side). Again, the analysis of deratings evolution enlightens the disruptive effect of new technologies.

Appendix B

Tables and figures

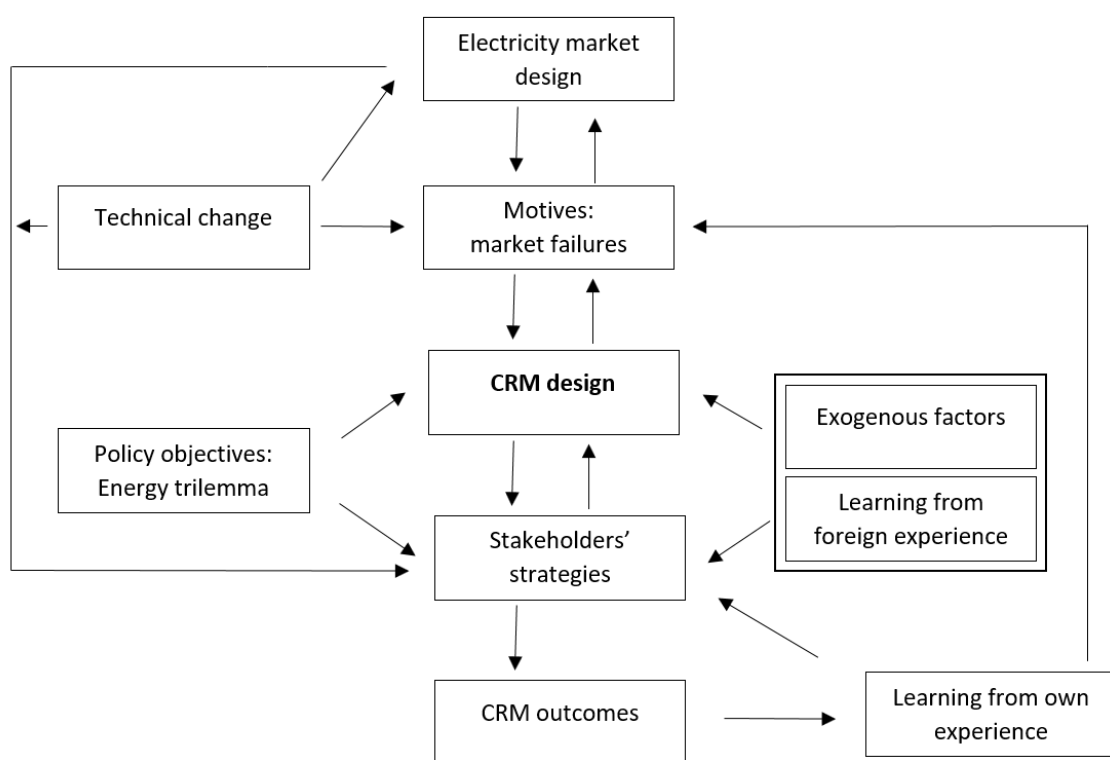


Figure B.1: Conceptual framework



Figure B.2: Cross Country learning example, source: [NYISO, 2011]

| | PJM (99-07) | PJM (07-) | ISO-NE (98-10) | ISO-NE (10-) | NYISO | MISO (09-12) | MISO (12-) | UK (90-01) | UK (14-) | France (17-) | Spain (97-07) | Spain (07-) | Ireland (07-18) | Ireland (18-) | Italy (04-) | Colombia (97-12) | Colombia (12-) |
|--------------------------|----------------|--------------|-------------------|-----------------|-------|-----------------|---------------|---------------|-------------|-----------------|------------------|----------------|--------------------|------------------|----------------|---------------------|-------------------|
| High level design | | | | | | | | | | | | | | | | | |
| Market | x | x | x | x | x | x | x | | x | x | | | | x | | | x |
| Volume | x | x | x | x | x | x | x | | x | x | | | | x | | | x |
| Centralized | | x | | x | | | x | x | x | | x | x | x | x | x | x | x |
| Contract | | | | | | | | | | | | | | | | | |
| Obligation | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | | x |
| 1 year Delivery period | | x | | x | | | x | | x | | | x | | x | | x | x |
| 3 Years Lag period | | x | | x | | | | | | x | | | | | | | x |
| Non-compliance penalty | x | x | x | x | x | x | x | | x | x | | x | | x | | | x |
| Market power mitigation | | x | | x | x | | x | | x | x | | | | x | | | x |
| Capacity Demand | | | | | | | | | | | | | | | | | |
| Missing Money \CONE | | x | | x | x | x | x | | x | | | | x | x | | | x |
| Demand Curve | | x | | x | x | | | | x | | | | | x | | | x |
| Market | | | | | | | | | | | | | | | | | |
| <i>Ex ante</i> clearing | x | x | x | x | x | x | x | | x | | x | x | | x | | x | x |
| Adjustment auction | x | x | | x | | | | | x | | | | | x | | | x |
| Product | | | | | | | | | | | | | | | | | |
| Market wide | x | x | x | x | x | x | x | x | x | x | x | | x | x | x | | x |
| Derating | | x | x | x | x | x | x | | x | x | x | x | x | x | x | | x |
| Secondary trading | x | x | | x | x | x | x | | x | x | | | | x | | | x |
| Non-conventional | | | | | | | | | | | | | | | | | |
| Interconnectors | x | x | | x | x | x | x | | x | x | | | x | x | | | |
| Rating | 9 | 16 | 7 | 16 | 12 | 10 | 13 | 3 | 15 | 10 | 5 | 6 | 6 | 15 | 4 | 3 | 15 |

Table B.1: Rating of designs

Chapter 2

What Do Models Tell Us About Capacity Remuneration Mechanisms? A Literature-Based Analysis of their Performance Compared to the Energy-Only Market

Abstract

Confronted with the difficult empirical assessment of capacity remuneration performance, numerous studies using numerical or analytical models compare alternative market designs –energy-only or capacity remuneration. However, the diversity of methods and results at use makes it difficult to derive a comprehensive view of the efficiency of capacity remuneration mechanisms (CRMs). A novel approach is developed to improve the comparability of literature results. Using a panel of papers that investigate different market designs, the energy-only market (EOM) results are used as a benchmark to normalize the conclusions. The 19 studies analyzed do not converge towards one simple conclusion. Surprisingly, nature of the model (model paradigms) has little impact on results. In line with the unresolved discussion on the performance of CRMs compared to the EOM in the presence of market imperfections, four main topics emerge: security of supply, welfare, price volatility, and the amplitude of investment cycles. Most studies in our panel agree on the efficiency of CRMs to reduce both price volatility and investment cycles compared to the EOM. For the security of supply (SoS), the effects are overall beneficial, although less consensual. However, improved SoS does not automatically translate into a higher consumer surplus, mainly due to heterogeneous definitions of SoS and surplus. With this respect, a discussion within the research community to develop a common approach and language would certainly help to advance the understanding of CRMs further and send clearer signals to power systems regulators.

2.1 Introduction

Chapter 1 has discussed the role of system heterogeneity (exogenous factors) in impeding efficient performance assessment. In this sense, performance indicators cannot empirically isolate the effect of market design. This is all the more problematic that it also prevents the thorough assessment of the impact of market imperfection on market performance.

As a matter of fact, several market imperfections undermine the EOM performance, especially in terms of investment incentives. Cramton and Stoft [2005] argue that price caps and/or market interventions generate "missing money"¹. As a consequence, the investments will always be inadequate. Although accurate scarcity pricing should solve the missing money problem, Cramton and Stoft [2006] consider that adequate reserve margins would suppress the scarcity rent, making marginal capacity deficiary. Indeed, as the scarcity rent is decreasing in the reserve margin, it is in the market players' interest to maintain a low reserve margin to boost profits [Keppler, 2017]. According to Cramton and Stoft [2006], the social cost of under procurement will thus always be higher than the social cost of over procurement because blackouts do not enter in the decision process of private actors. The issue of "missing markets", as described by Newbery [2016] exacerbate the tendency for under-procurement. It mainly refers to the incompleteness of markets and the lack of hedging possibilities that negatively affect investment opportunities.

In this context, numerous scholars doubt of the optimality of the theoretical first best equilibrium –the EOM– and advocate for market interventions such as CRMs implementation to restore investment incentive. They are designed to (at least partially) correct for missing money and missing markets issues by restoring the investment incentive (see chapter 4 for a discussion on risk) through granting a fair revenue for the SoS services provided. In doing so, they are expected to reduce both wholesale price levels and volatility while restoring a favorable investment climate². The unresolved issue is to know which one of an EOM or a market with a CRM would be more efficient in limiting the dead-weight loss generated by market imperfections. In this sense, the market performance of a CRM can be regarded as the ability to (i) limit the loss of load probability (LoLP) (ii) at a reasonable cost. In other words, the welfare is increasing in available capacity (avoided black-outs), but decreasing in system costs (energy plus capacity). Consequently, proving the superiority of one design over the other requires the assessment of both the variation in capacity and the variation on consumer welfare, or, at least, end-user prices. With respect to the actual functioning of the CRM, intermediate metrics inform on the credibility of the underlying reasoning. Although reduced price volatility and lower investment cycles

¹Joskow [2007] explains the notion of missing money as follow: "Spot wholesale electricity market prices for energy and operating reserves will simply not be high enough to cover both the operating costs and the capital investment costs (including an appropriate risk-adjusted cost of capital) required to attract new investment in long-lived generating capacity to support a least-cost generation supply portfolio consistent with mandatory reliability criteria."

²The dynamics are slightly different in the case of strategic reserves and operating reserve since investment incentives still rely on efficient scarcity prices (see section 2.2.2).

do not represent explicit objectives of CRMs, they are often presented as improvements to market conditions. Indeed, the former reduces the need for hedging instruments, and the latter lowers deviations from the targeted capacity: those outcomes can become highly beneficial when actors are risk-averse, for instance.

Due to the limited comparability of existing experiences, this question remains unsettled from an empirical standpoint. Most conclusions from the modeling literature are not comparable either because of the diversity of hypotheses necessary to build a realistic model. This chapter seeks to contribute to this discussion using a novel approach in terms of literature analysis. Instead of summarizing literature results, I consider a sub-sample of papers that all consider both the EOM and at least one CRM. The EOM being the theoretical first-best and a recognized benchmark [Joskow, 2010], it thus normalizes the results of each paper, making their conclusions more directly comparable than it would otherwise be. In this framework, each paper considers a set of specific assumptions and assesses the relative performance of a market with CRM compared to the EOM benchmark under the same hypotheses. A convergence in conclusions over the papers analyzed would suggest not only a probable superiority of one design over the other but also its robustness to specifications (i.e., market imperfections, uncertainty, and design). On the contrary, disagreement in the conclusions supports the hypothesis that model assumptions drive the conclusions as much as system heterogeneity is suspected of impeding cross-system comparison from an empirical perspective.

Based on nineteen papers that compare CRM performance against the EOM benchmark, this chapter is organized as follows. Section 2.2 proposes to classify the relevant papers according to three main characteristics: (i) the model paradigm at use, (ii) the type of CRM investigated, (iii) the market imperfections investigated. Papers' characterization provides insights into the choices made by authors in this stream of literature, which is useful to nuance the results presented in section 2.3. Mainly, CRMs are found to reduce both price volatility and investment cycles. The implementation of a CRM most often increases the security of supply (SoS), but full consensus has trouble to emerge. However, the effect on the consumer surplus is unsettled. Ultimately, section 2.4 discusses the findings and highlights what needs to be cut short. Indeed, where CRMs are implemented to ensure SoS on behalf of captive consumers, it is unreasonable to keep on wondering about the effect on consumer surplus.

The focus on comparative studies with an EOM benchmark re-centers the scope of this analysis compared to previous versions (see Scoufflaire [2018]) to focus on this specific research question³. It also differs from the recently published literature review. Bublitz et al. [2019] seek to synthesize existing knowledge on CRMs: "[their] article aims to guide both, new entrants and advanced researchers, through the field of electricity market design by providing a comprehensive and up-to-date overview of market design options". In this

³This chapter is in the continuity of the previous version, but conclusions are not directly comparable given changes in the papers considered and the evolution of some analysis criterion.

sense, the two papers provide complementary answers to the difficulties of the literature to provide stakeholders with key take-away messages on CRMs need, performance, and design.

2.2 EOM versus CRM: approaches and research questions

2.2.1 Model paradigms

The implementation of CRMs raises various questions, precisely because the EOM should be more efficient in the standard perfect competition paradigm (refer to the general introduction for thorough discussion). Specific tools of analysis are required because regulatory changes are often made parsimoniously, complicating the identification of the performance of market design changes both in perfect and imperfect competition. Keeping our analytical framework as simple as possible, we reference the papers by modeling paradigm. Following Koppelaar et al. [2016], we separate optimization models from simulation ones: each of them responds to a specific power market problem. Optimization models can either take the central planner's or the firms' perspective. The latter is well suited for imperfect competition analysis. With respect to simulation models, agent-based models focus on the market participants' behavior while system dynamics highlight the state changes over time. While Koppelaar et al. [2016]'s classification is general and suited for both numerical and analytical models, the two streams of literature are different in form and objectives: the choice is made to consider analytical models aside –as a fifth category. Indeed, analytical models do not necessarily require parametrization and partially abstract from power systems complexities. This allows them to derive unambiguous results with respect to the research question.

Thanks to their stylized representation, analytical models are easy to interpret and lie on a reduced number of assumptions. They thus drive powerful messages. They also are the core of all numerical models: the standard theoretical literature inspires the objective functions and the market organization assumed. They complete each other: numerical models were developed to answer more complex problems that analytical models were unable to solve. As a counterpart, they often need to resort to case studies to derive clear conclusions. Both are thus needed to convey a message efficiently.

As their name suggests, optimization models lead to the optimal solution of the problem at stake: they solve the objective functions under constraint. Where economic theory believes the agents to be rational, and perfect competition to lead to optimality, such models are well suited to derive optimal market outcomes. They are also in line with the system operators' objective: welfare maximization. Under standard hypotheses, this is equivalent to minimizing the cost of supply under the constraint of the security of supply. The central planner perspective provides clear conclusions on the least cost mix that could emerge in a given regulatory framework. The latter is often represented in the model through the model constraints. For instance, a CRM is most easily implemented

under a capacity constraint –not only– that forces the optimal solution to account for a given reserve margin. While this implicit representation of CRMs is in line with theory, it only provides a partial view on the problem for often disregarding the investment decision process.

Driven by the liberalization of power markets, a new range of model paradigms has emerged as an alternative to the central planner perspective: firm oriented models. We, however, consider a slightly broader definition than Koppelaar et al. [2016] to include all firm oriented analyses as a default category⁴ that include different approaches such as partial equilibrium, game theory and finance approaches. If electricity prices somehow still relate to a welfare perspective⁵, the introduction of market imperfections shifts the focus from the system as a whole to the agents' preferences. Well-suited to investigate firms' behaviors, firm-oriented models can maximize the profits or any other objective function. The ability to represent strategic behaviors and complex preferences is critically useful in present power systems. When the equilibrium conditions are investigated, they can be sub-optimal (Nash equilibrium) as a consequence of the firms' behavior and market clearing procedure.

In turn, simulation models started being used as a complement to optimization results. They can accurately compare policy instruments to cut out the inefficient ones. The capacity of such models to highlight decision dynamics naturally steer them in risky and uncertain environments. Agent-based models go further in the description of agents' behaviors by defining a decision rule that they follow. Agents can use information in their decisions, but also to learn from their own actions and those of others. In this decentralized framework, the use of uncertainty is relatively common to allow for information uncertainty in the decision process. Competition is not necessarily perfect neither since each agent has its own decision algorithm. The order in which the agents' act does matter because they might be able to seize opportunities as first movers or even aggregate additional information as last movers. As it now appears clearly, this is the category of models that are the most focused on decentralized decisions and how the agents' decisions might be individually affected by changes in the market design. More than the potential equilibrium outcome, the evolution of the market will reveal much about the feasibility of policies given the initial situation. The main criticism of this representation lies in investment strategies. They are sometimes considered too simplistic compared to reality [Newbery, 2012]

The second category of simulation models is system dynamics, also called "stock-flow" models. In this paradigm, the state changes are at the core of the analysis. Instead of defining the decision rules as in agent-based models, system dynamics models focus on the relationships between the entities. In doing so, it is also well suited to model complex systems with feedback effects such as the interdependency of the energy and capacity

⁴Indeed, the other categories considered (Welfare maximization, agent-based, system dynamic and analytical models) are usually well defined and named within the model description.

⁵For instance, auctions clearing often maximize the sum of buyers and sellers surpluses.

markets. The relationships can be either positively or negatively correlated, and, more importantly, happen simultaneously or with delay. The causal relationships allow for accurate representations of investment decisions [Petitet, 2017].

All in all, optimization models usually take the environment as given and derive the optimal decisions. On the contrary, simulations models exogenously set the decision process and provide the path towards equilibrium. Applied to the security of supply objective, the difference between simulation and optimization models is conceptual. The former often assesses the ability of a system to meet a target while the latter considers the cost of doing so. Nevertheless, each of the five modeling paradigms provides an additional brick to the understanding of the electricity market, and especially CRMs. Obviously, depending on the modeler's objective, the models often grow much more complicated than this general view suggests, the frontier between them then becomes porous. To highlight the message rather than the mean, all papers were fit into one of the five categories.

| Welfare optimization | Firm oriented | agent-based | System dynamics | analytical models |
|-------------------------|---|--|--|---|
| Bucksteeg et al. [2019] | Höschle et al. [2017]* de Maere et al. [2017] Traber [2017]* Hach and Spinler [2016] Kamalinia and Shahidehpour [2010]* | Bhagwat et al. [2017] Bhagwat et al. [2016] Keles et al. [2016] Iychettira et al. [2014] Genoese et al. [2012] | Petit et al. [2017] Hach et al. [2016]* Hary et al. [2016] Cepeda and Finon [2011] Assili et al. [2008] de Vries and Heijnen [2008] | Léautier [2016] Bajo-Buenestado [2017] |
| 1 | 5 | 5 | 6 | 2 |

* no uncertainty as discussed in 2.2.3

Table 2.1: Model paradigms

Table 2.1 provides a synthetic view on the model paradigms used in the papers we consider: the colors provide a reading key for coming tables. Amongst nineteen articles, six of them use optimization methods with a preference for microeconomic models (five firm-oriented models) compared to system cost minimization (only one). This uneven balance reflects the increasing concerns about strategic behavior in CRMs, which are more easily considered in firm-oriented models. For similar reasons, a vast majority of the papers at hand resort to simulation (eleven), mainly through system dynamics (six), but also adopting agent-based models (five). Considering the size and complexity of power systems, analytical models are often set aside: only two papers in our panel go for this methodology.

In comparison, Bublitz et al. [2019] consider a slightly different classification with four main categories: analytical models, single-firm optimization, agent-based, and system dynamics. While the two latter should be reasonably similar, the "analytical model" category is broader⁶, and single-firm optimization seems more restrictive than our firm oriented category. Naturally, Bublitz et al. [2019] include a much broader literature for not being limited by the need for a benchmark. Yet, they also include single-firm optimization, agent-based, and system dynamics in a similar proportion. If both panels proved to be representative of the existing literature, it would attest to a balanced interest of scholars

⁶Mainly, this chapter separates numerical models from purely analytical models where Bublitz et al. [2019] abstract from the resolution method to focus on the formulation of the problem.

towards the question of market outcomes and dynamics of convergence. In line with the issues of investment incentives as well as market power that repeatedly appear in CRMs discussions, the model paradigms that naturally consider uncertainty and imperfect competition are preferred. This being said, welfare maximization and analytical models are still at use with recent publications, which confirms the complementarities between the paradigms and the capability of each model to adapt the research question.

2.2.2 CRMs

In the EOM, the scarcity rent is necessary for cost recovery. As such, it drives investment incentives. In a CRM framework, this scarcity rent is either increased to reflect actual scarcity or partially suppressed and replaced by capacity remuneration. At the aggregate level, it can have important redistribution effects that affect market outcomes: by altering the individual investment incentives, the CRMs are likely to modify the resulting mix as well as system costs. In turn, prices and security of supply levels will be different. This drives the interest of scholars, who often compare the different CRM designs to set out their relative benefits. A taxonomy has been developed over time to discriminate the designs that rely on different dynamics [Henriot and Glachant, 2013; Meulman and Méray, 2012; Hogan, 2005]: the capacity payments (CP), the capacity market (CM), the reliability option (RO), the contract-for-differences (CfD), the strategic reserve (SR) and the operating reserve demand curve (ORDC).

In a capacity payment (CP) scheme⁷, the level of the remuneration is set by the public authority. Given this amount, the actors will consider the opportunity to invest: quantity (reliability) will be an outcome. CPs are often market-wide, but can also be targeted towards specific units as it is the case in Spain. In models, the level of payments is often set exogenously.

The capacity market (CM)⁸ is rather a volume-based mechanism: the quantity is defined by the public authority in line with the reliability target. Then auctions are organized to procure the corresponding quantity: the price results from market clearing. To implicitly mimic this design, a capacity constraint forcing the available capacity to exceed demand at all times is often implemented. Alternatively, the reliability target -or capacity demand- can also be used directly within the model to simulate an auction. The reliability options (RO)⁹ are financial call option contracts. On the one hand, the contractor is hedged against high prices. The contracted amount of energy will be delivered at a given strike price every time the spot price rises above its level. On the other hand, electricity generators receive a payment in exchange for delivering electricity below market prices –at scarcity–. In a sense, RO can be seen as one-way contracts-for-differences (CfD) where consumers hedge against high prices. As discussed in Cepeda and Finon [2011] and Léautier [2016], RO and CM can resume to the same mechanism under given design options.

⁷Spain, Italy.

⁸PJM, ISO-NE, NY ISO.

⁹Colombia, Ireland.

For instance, CMs are often modeled together with a capped electricity market while the strike price in RO acts as a *de facto* price cap if all units are contracted. It thus makes sense to gather those two designs in one category (CM/RO)¹⁰ to gain in readability.

While the RO is an hedging tool for the consumers as much as a reliability product, contract-for-differences (CfD)¹¹ as a CRM rather refers to the "missing market" concept: investors want to avoid market risk. In this sense, it can hedge against low prices (one-way CfD) or provide generators with a fixed price (two-way CfD). When centrally procured, it is often targeted towards specific technologies such as green technologies in the UK. As discussed in de Maere et al. [2017], CfD and hedging instruments in general boost market performance. If improving hedging possibilities increase investment incentives in the markets, they are not unanimously considered as CRMs *per se* since they may, or may not result from market intervention.

The strategic reserve (SR)¹² procures extra capacity out of the market so the reserve margin is secured. When contracted in the SR, the units are not able to take part in the spot market anymore. They only run at scarcity and get refunded their costs when it happens. Usually, the SR –where cost recovery is certain– is thus composed of generators that do not expect market-based profitability. Per definition, the strategic reserve will not remunerate all the capacities but only a predefined quantity, as deemed necessary to meet the reliability target. Lastly, the operating reserve demand curve (ORDC)¹³ intends to restore the market price signal through an explicit valuation of reliable capacity (reserve). Instead of separating the units providing energy from those providing reserve (SOS), the ORDC values the reserves, a "real-time price adder" complements the energy price to restore the scarcity signal. In this framework, times where energy is cheap while there is reserve shortage disappear: it is inherently a short term scarcity price signal, but aims explicitly at restoring investment incentives. Consequently, ORDC classification as a CRM is debated. Although SR and ORDC operate differently, the two types of reserves stand out from the other types of CRMs for not trying to reduce the dependency on scarcity pricing. Instead, the former keeps unprofitable plants online to ensure SoS while leaving investment incentives to the electricity market. In turn, the ORDC seeks to improve scarcity pricing to ensure an efficient price signal. As a result, the two designs both improve investment incentives through the spot price signal and will thus be considered together (SR/OR) in the remainder of this chapter.

Although each type of CRM considered can be modeled in separate ways, we try to fit all investigated policies into the framework described. Fortunately for the sake of our analysis, some studies include more than one type of CRM, which allows for fruitful conclusions. Once fit in one of the four categories, the whole panel lead to a total of thirty-

¹⁰As none of the paper assumes market power on the demand-side, discriminating between centralized and decentralized mechanisms is not necessary either.

¹¹The UK.

¹²Belgium.

¹³ERCOT, based on Hogan's proposal.

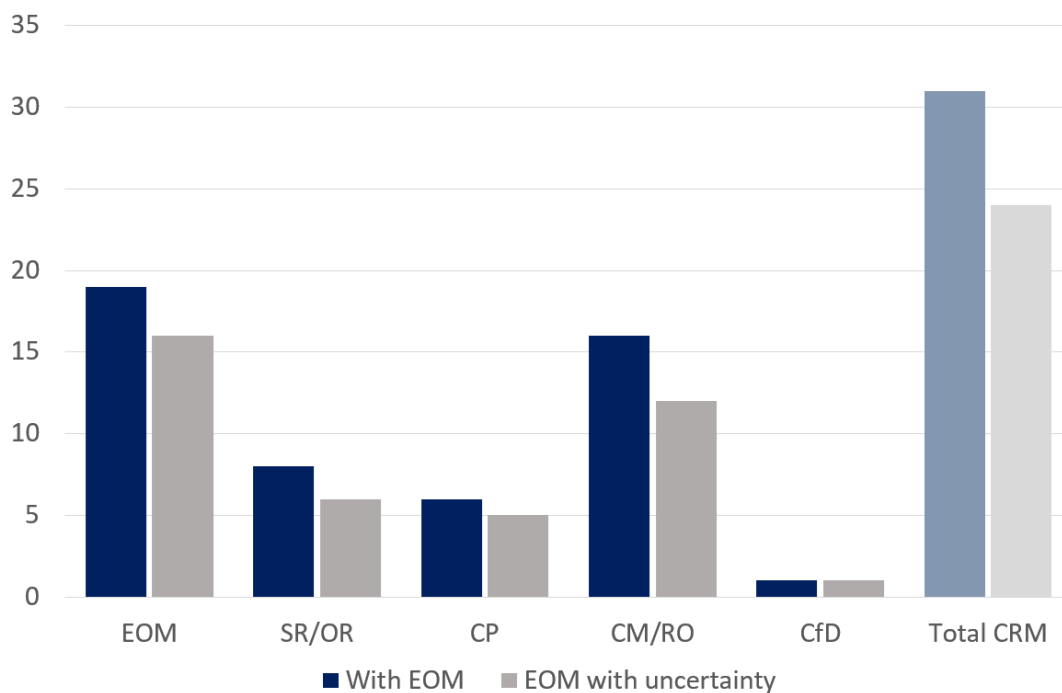


Figure 2.1: Types of market organization investigated (number of papers)

one policies considered in the panel of nineteen papers (see figure 2.1). Among those, the most studied CRM designs are, without surprises, the market based-procurements: CM/RO are discussed in sixteen occurrences (i.e., in almost all papers). As highlighted in chapter 1, CRMs actually seem to converge towards this form of design, which explains its popularity in the literature. SR/OR (eight) and CP (six) are less investigated as market designs. CfD remains an outsider as only de Maere et al. [2017] consider such an option. Some papers might also consider interconnected markets with different market designs. In this case, the benchmark remains the EOM, and complex combinations of designs are excluded. For instance, in Bhagwat et al. [2017], the reference case has two interconnected EOM, while CRM cases considered would respectively have an SR or a CM in one country while the other remains an EOM. The case where the two countries implement a different CRM is disregarded. Similarly, Bucksteeg et al. [2019] consider a Europe-wide model with different degrees of integration: EOM for all systems, capacity markets in selected countries, capacity markets in all countries, and one capacity market for the whole European system (which implies a lower reserve margin thanks to de-correlated peak periods in the different countries). In this context, only results for a coordinated implementation of CRM over Europe are presented in this paper. In Cepeda and Finon [2011] provide five cases, but only the two interconnected EOM and the two interconnected forward markets are selected for this chapter. The interested reader can always refer to chapter C or the papers themselves for further details on their conclusions.

2.2.3 Uncertainty and security of supply

As discussed in Parsons and De Sisternes [2016], the differences between the market designs are insignificant in perfect competition. However, when markets are incomplete, uncertainty brings out the complexity of the problem at stake as well as the differences in market outcomes. With this respect, we can define two kinds of uncertainty: the information-related uncertainty and the exogenous uncertainty. The former here refers to the imperfect information of the regulator with respect to the conditions of intervention (parameters) that restore the optimum. For instance, the acceptable level of scarcity is based on the public authority's best estimate of optimal scarcity. In a framework where demand is relatively inelastic for technical reasons, accurate inference of the value of lost load (VoLL) is more of a lucky guess¹⁴ [Cramton et al., 2013]. Indeed, most markets are capped either explicitly to limit market power or implicitly to avoid black-outs¹⁵ [Joskow and Tirole, 2007]. Conceptually, the cap should form a threshold from which an outage is considered as less costly system-wise than the electricity supply. What is an educated guess for the public authority cannot be a homogeneous belief amongst modelers. The public authorities much discuss this regulatory uncertainty all around the world because it does affect the efficiency of the CRM designs. In models, the choices in terms of VoLL –which may or may not also be used as a price cap– will be reflected mainly in the consumers' surplus (Loss of load valuation) and end-user prices (cost of supply at scarcity), but also affect investment. In this context, it is worth mentioning that the VoLLs considered in our panel range from undiscussed to 20 000€/MWh. When the VoLL is debated in a paper, it is likely to be set around 9 000€/MWh. The second type of uncertainty relates to the existence of different states of the world that cannot be perfectly anticipated, such as the level of demand, plant outage, renewable production, or commodity prices.

Because there is not much that can be done about this information related uncertainty, the public authority herself acts as if its expectations were accurate, seeking to reach the identified optima. In this sense, it operates as in an omniscient central planner perspective, and uncertainty does not specifically play an important role. What does matter, however, is knowing the least cost solution. This actually makes a very relevant framework of analysis to highlight the trajectory of markets with and without CRM considering that system operators do often procure capacity as central planners¹⁶. In this stream of analysis, Kamalinia and Shahidehpour [2010] consider capacity payments and locational capacity payments (LCP) under no uncertainty and finds that the "proposed LCP provides efficient solution" (compared to the EOM). Considering a CM, an SR, and a reserve obligation (disregarded), Traber [2017] insists on the fact that the impacts of a given policy largely depend on the existing mix and its evolution. For Höschle et al.

¹⁴The VoLL is often described as a non-linear function in duration that differs between consumers groups. Royal Academy of Engineering [2014] finds empirical ground for this assertion.

¹⁵In a situation of scarcity, system operators take measures to avoid outages, *de facto* reducing the actual scarcity in the market.

¹⁶PJM, ISO-NE, National Grid etc.

[2017], "SRs [...] introduce large inefficiencies [...] [centralized CM] yields a sufficient high reserve margin at lowest cost.". Hach et al. [2016], while leaving uncertainty to further research, concludes that "results [...] suggest that capacity markets can decrease the long-term bill of generation because, through deliberate overcapacity, they prevent loss of load occasions and reduce strategic bidding".

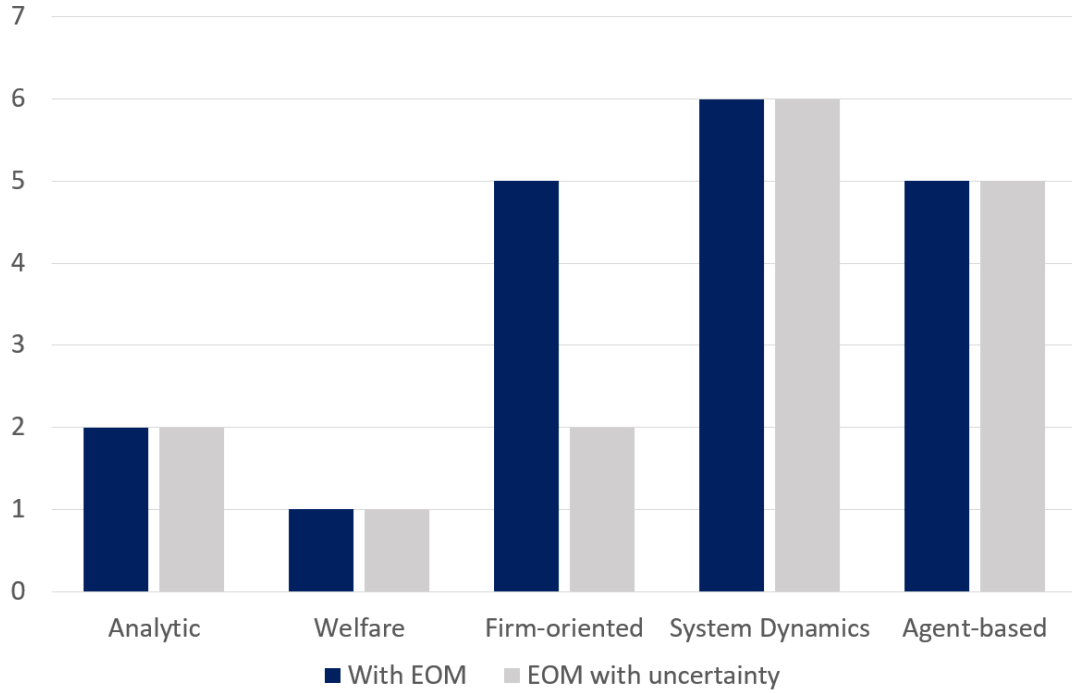


Figure 2.2: Model paradigms and uncertainty (number of papers)

Exogenous uncertainty can also be effectively accounted for in agents' decisions. Considering the dependency of investment incentives to uncertainty¹⁷; numerous papers decide to include this perspective in their analysis. Often, this results in a shift in the focus: the spotlight is on market players instead of a central planner. If uncertainty is often included for its impact on revenues and investment incentives, there are various ways to account for it explicitly: plant availability, renewable generation, demand or fuel prices or even electricity prices themselves can be unpredictable. With another approach, bounded rationality implicitly accounts for the uncertain future market outcomes. In line with their capabilities, all simulation models account for a certain form of risk or uncertainty, but the other model paradigms are not left out (see figure 2.2). For instance, Bucksteeg et al. [2019] accounts for uncertainty *ex post*. Indeed, because their model does not allow for blackouts, the energy-only market remains cheaper in terms of system costs but results in higher price volatility. However, when post-processing results to subject the mix to additional uncertainty, the hierarchy is reversed, and the energy-only market ranks last both in terms of LoLP and system costs¹⁸.

¹⁷For instance, system operators use complex statistical models to assess the capacity corresponding to the relevant loss of load probability RTE [2014].

¹⁸the post-process values the blackouts.

Without necessarily considering explicit uncertainty, bounded rationality reflects the idea that market actors cannot effectively predict the future. With this respect, Assili et al. [2008] find "the EOM [to be] both more expensive and less reliable" in a framework of bounded rationality. According to Genoese et al. [2012], capacity payments lead to higher investments and lower prices when a steady portfolio constraint drives investments under bounded rationality. According to Hach et al. [2016], "the introduction of CM has a positive effect on the market in terms of affordability and reliability" when rationality is bounded. In Keles et al. [2016], they conclude that under bounded rationality, the EOM works for short-term, but its advantages decrease in the long term when the CM ensures reliability in the long term. Bhagwat et al. [2017] uses an agent-based model with bounded rationality to compare the efficiency of CM and SR in an interconnected framework. They find that "interconnections do not affect the effectiveness of a capacity market, while a strategic reserve is affected negatively".

The remainders of the papers explicitly represent uncertainty. For instance, de Vries and Heijnen [2008] also conclude that all CRM alternatives (CP and RO) perform better than the EOM in terms of prices and shortages when demand is uncertain. In turn, the various uncertainties (demand, market, outages, and maintenance) considered in Cepeda and Finon [2011] lead to the conclusion that "the forward capacity market react better to demand and supply shocks" (compared to CP and EOM). Comparing a CM with the EOM default design, Iychettira et al. [2014] conclude that the capacity market ensures generation adequacy (hypothesis 1) when uncertainty is applied to both demand and fuel prices. Hary et al. [2016] find the CM to be more efficient than both the EOM and the SR when demand growth is uncertain. Considering a real option analysis with stochastic electricity and gas prices, Hach and Spinler [2016] "show that capacity payments are one possible way to induce investment in peak-load generation". They conclude that both the CM and the SR do improve the security of supply and reduce consumer costs. In a two-stage analytical model, Bajo-Buenestado [2017] finds the CP to reduce the LOLE compared to the EOM when future demand is uncertain. Similarly, Léautier [2016] considers that Hogan's strategic reserve (ORDC) should be selected if the energy market is competitive, but CM and RO should be implemented otherwise. Using an agent-based model under uncertain demand growth and fuel prices, Bhagwat et al. [2016] compare the EOM with an SR with and without stochastic renewable in-feeds. The SR is found to improve both SoS and consumer welfare unconditionally under renewable uncertainty (results are subject to the valuation of lost load otherwise). Petit et al. [2017] compare the effect of short term weather variations with and without risk aversion. The EOM efficiency is deterred when agents are risk-averse. de Maere et al. [2017] investigate the effectiveness of different policies in incomplete markets with demand uncertainty: "CfD and RO effectively complement the EOM in order to mitigate risk [...] the forward capacity market reduces hurdle rates".

All in all, most of the papers investigating CRM design do account for uncertainty, or at least imperfect foresight. Risk aversion and strategic behavior are other tools at hand to

mimic market conditions; they will only be considered implicitly in the following section. The diversity of market imperfections and uncertainties that can be considered creates rich insights, but most readers will struggle to derive a clear takeaway message from this literature review (or even from the more detailed version that can be found in chapter C). The following section precisely banks on the existence of an EOM scenario -used as a benchmark- in each paper to normalize the performance of their CRMs counterparts and derive comprehensive conclusions¹⁹.

2.3 Results

As discussed previously, CRMs seek to correct the tendency of EOMs to under-invest. Remunerating SoS *per se* lowers the need for hedging instruments through a limited reliance on a volatile scarcity rent, limiting wholesale price volatility. If this should be observed under CP, CM, RO, and eventually CfD, it is less straightforward with SR or OR –which investments rely on the electricity price signal. The additional investments induced by the CRM should reduce the risk of outage. A natural consequence of both the higher reserve margin and the reduced uncertainty on a future profitability gap would be the reduction of the amplitude of investment cycles. By reducing phases of over-investment, savings are made on the cost of unneeded units. Complementarily, avoiding under-investment lowers the risks of costly blackouts. The main unknown in this reasoning is the actual cost for end consumers. With this respect, the metric displayed for consumer surplus represents the conclusions of the paper at hand: some will include –and value– the energy not served, others will only discuss the effect of CRMs on end-user prices. This section will thus focus on those four main elements which are most broadly concluded on: price volatility (price standard deviation or volatility), amplitude of investment cycles, security of supply (variation in capacity/investments), consumer surplus (variation in total cost of electricity and eventually in the total cost of energy not served). Naturally, summaries are here represented abstracting from the complexity and nuance presented by the authors in the original paper. Indeed, it is common to perform sensitivities to test the robustness of the results: they are not accounted for either in table 2.2 or in figure 2.3 to 2.6.

As hypothesized, the roughly twenty studies analyzed do not converge towards one simple conclusion: results depend on the market imperfections considered. Surprisingly, modeling paradigms drive the research question but have little impact on conclusions. For instance, simulation models are usually more suited to conclude on investment cycles than optimization models, but there is no evidence that one class of models consistently finds different results from the others (see table 2.2).

¹⁹To understand the intuition behind the idea of normalization some readers might find helpful to think of empirical econometric studies, which sometimes resort to matching methods to derive causality. Thanks to the EOM benchmark provided by each paper, the matching is perfect between the control group (EOM) and the treated group (CRM).

With regard to investment cycles and price volatility/ risk, the literature leaves no doubt on the ability of CRMs to be beneficial (see figure 2.3 and 2.4). When these aspects are studied, all papers find CRMs to lower price volatility and the amplitude investment cycle. As discussed by Hary et al. [2016], SRs do reduce under-investment phases but has little impact on over investment. On the contrary, CM/ROs seem to stabilize the reserve margin and the energy prices [de Vries and Heijnen, 2008]. CPs tend to reduce the number of scarcity events (price spikes) while in SR/OR, the reduction in price volatility is limited and contingent on the activation price of the reserve [Bhagwat et al., 2017] as well as the mix evolution when units do enter the reserve [Traber, 2017].

This is a strong result for two reasons. Considering that the reserve margin is often an outcome²⁰, and each model paradigm represents the market and the investment decision in a different way, a consensus reflects the robustness of the conclusion. Second, in a world of risk-averse agents where investors consider different markets and not the power sector alone, market risk reduction –lower price volatility– should indeed attract investments [de Vries, 2004].

Nonetheless, conclusions regarding SoS are less consensual. Indeed, the debate on CRM need and efficiency leaks out from the literature review. In table 2.2, it is clear that CRMs are most often found to be efficient in increasing the security of supply, and there does not seem to be one model paradigm that would favor specific results. Even the consideration of a certain degree of uncertainty does not seem to have an impact on the positive outcomes of CRMs on SoS. Indeed, only three papers conclude in a decrease (or equal level) of SoS under CRM, and most of them consider an efficient EOM –the first best equilibrium– as a benchmark. For instance, Léautier [2016] compares the ORDC and the reliability options to the efficient EOM. Proposition 4 states that the "[ORDC] is isomorphic to standard peak-load pricing": under-investment will occur unless the market is competitive and the price cap never binding. Similarly, the RO/CM can only reach optimal capacity under given conditions. Furthermore, Petit et al. [2017] finds ambiguous results where the improvement on SoS depends on the level of VoLL used and the degree of risk aversion considered²¹. With respect to de Maere et al. [2017], they find that the RO and CfD would, at best, provide a similar number of scenarios with scarcity than the complete market, while a CM can decrease this number. The fact that all papers interested in CP conclude in an increase of investment is partially explicable by modeling decisions. Indeed, CP can be modeled as exogenous payments that come on top of other revenues: higher revenue expectations naturally lead to higher investments all other things equal.

²⁰Most studies which conclude on investment cycles and price volatility are using simulation models (see table 2.2).

²¹Actually, most of the results depend on the parameters of the model, the intuition behind is well discussed in the original paper.

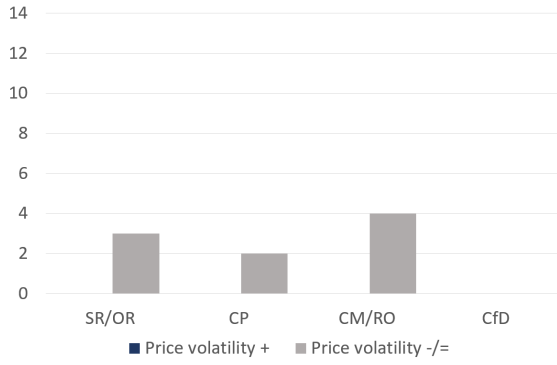


Figure 2.3: Price volatility results (number of papers)

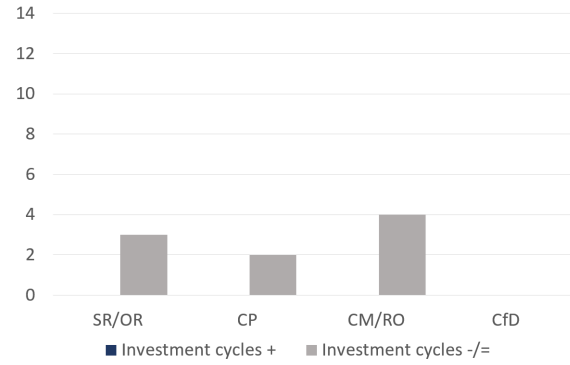


Figure 2.4: Investments cycles results (number of papers)

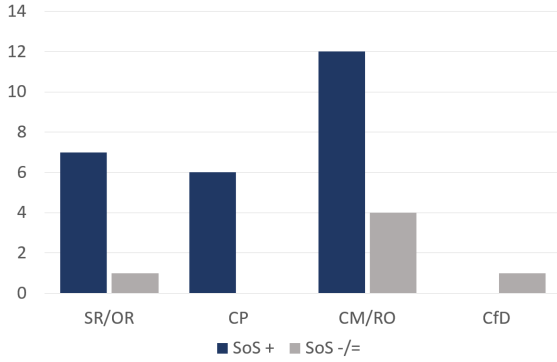


Figure 2.5: Security of supply results (number of papers)

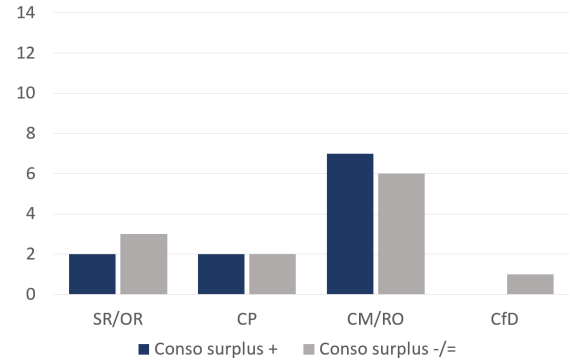


Figure 2.6: Consumer surplus results (number of papers)

Only half of the studies (see table 2.2) that analyses the consumer surplus –or the consumer bill– find that CRMs increase their well being. This does appear to be more related to the assumptions on demand than the model paradigm adopted or even the type of CRM implemented. As explained for the security of supply, papers using an efficient EOM as a benchmark are likely to find a decrease in the consumer surplus due to the cost of CRMs. In addition, CRMs are found to be less efficient in terms of consumer welfare when the demand is assumed as elastic [Traber, 2017], if curtailment is not allowed [Bucksteeg et al., 2019]²² or if the outages are not valued in monetary terms [Iychettira et al., 2014]. Even studies with similar levels of VoLL might as well find contradictory results with this respect. Overall, it is difficult to discuss the causes of such a divergence because welfare considerations are usually not at the core of the analysis and there is no consensual valuation of involuntary rationing or DR.

If an agreement is found on price volatility and investment cycles reduction, less than a third of the papers considered discuss such topics. On the contrary, SoS is almost

²²In a post-pocess, Bucksteeg et al. [2019] investigates the loss of load probability in each scenario and concludes that avoided outages under CM more than compensate for the cost of the measure.

systematically discussed in the papers. Yet consensus has trouble to emerge on the effectiveness of CRMs to ensure SoS. Against primary intuition, the improvements in SoS are not always paired with increases in the consumer surplus. Preexisting debates on electricity consumer surplus explains most of the disparities: the energy not served is not systematically valued and, when it is, the VoLL remains non-consensual.

2.4 Discussion

The present study aims to draw comprehensive conclusions out of the broad modeling literature on CRMs. Irrespective of the research question or the modeler decisions, the first requirement to select the papers is the inclusion of a benchmark. To be able to compare the results, all the papers included in this study confront at least two market designs, one of them being an EOM, the other a CRM. Reasoning in differences compared to the benchmark –EOM– creates normalized results over all of the papers. We are then able to directly use the authors’ conclusions on which design is considered as superior to which other. This allows us to disregard most of the hypotheses that might differ from one paper to the other, so to make a robust inference. The results are then discriminated against by the type of CRM considered in each paper to highlight potential outcome differences between the possible designs.

In this chapter, 19 papers are analyzed. Obviously, more were read and excluded -with regret- for not having an EOM benchmark. Amongst those papers, several developed an alternative design for a given country, the existing CRM being their benchmark, they were also more likely to represent a world without uncertainty. Although an increased panel size would bring about more robust conclusions in terms of CRM performance, the selection criterion is more restrictive than initially anticipated. In addition, 19 papers already allow for powerful insights. Model paradigms are discussed as well as the key assumptions such as the level of VoLL, the uncertainty, the investment drivers and benchmark definition, creating a useful framework of analysis for this diverse and complex literature.

If a consensus is found on price volatility and investment cycles reduction, only six studies out of nineteen conclude on the first²³ and even fewer on the second. On the contrary, SoS is almost always discussed in the papers, yet consensus has trouble to emerge. This mainly relates to the market imperfections considered. The efficiency of complete markets in perfect competition partially explains de Maere et al. [2017], Léautier [2016], and Petit et al. [2017] results where CRMs are commonly found less efficient than the EOM. As a corollary, an increase in SoS results either from an inefficient EOM or over-investment in the CRM case (compared to optimality) –which might be the objective of a cautious public authority. In this framework, the overwhelming majority of papers find capacity mechanisms to increase the level of security of supply (SoS).

²³This number would actually be higher if conclusions with respect to the evolution of the size of the scarcity rent or the dependence on this component for profitability were considered. Yet, no study suggests those could increase.

Against primary intuition, the improvements in SoS are not always paired with increases in the consumer surplus, especially when the increase in well-being is not accounted for. This relates to preexisting debates on electricity consumer surplus estimation: there is a trade-off between the cost of electricity (easily valued) and the costs of involuntary rationing or DR (not easily valued). Else, the SoS issue would be easily solved through a discrimination between the consumers as prescribed by Caramanis [1982]. As consumer surplus is central in the decision to implement a CRM or not, an open discussion on its representation is necessary to derive policy recommendations. This is all the more needed that CRMs are implemented on behalf of captive end consumers: not knowing whether it is actually surplus improving is an issue that needs to be resolved. Further research could include a more in-depth comparison of the representation of consumer surplus in the literature in order to set out the different paradigms at use and derive potential best practices.

| | SoS | Cons. Surplus | Volatility | Inv. Cycles |
|-----------|---|---|--|---|
| SR/OR + | de Vries and Heijnen [2008] Hary et al. [2016] Keles et al. [2016] Bhagwat et al. [2016] Bhagwat et al. [2017] Höschle et al. [2017] Traber [2017]* | Höschle et al. [2017] Bhagwat et al. [2017] | N/A | N/A |
| SR/OR -/= | Léautier [2016] = | de Vries and Heijnen [2008] Traber [2017]* Léautier [2016] | de Vries and Heijnen [2008]= Bhagwat et al. [2016] Bhagwat et al. [2017] | de Vries and Heijnen [2008] Hary et al. [2016] Bhagwat et al. [2017] |
| CP + | Assili et al. [2008] de Vries and Heijnen [2008] Kamalinia and Shahidehpour [2010]* Hach and Spinler [2016] Bajo-Buenestado [2017] Genoese et al. [2012] | Assili et al. [2008] de Vries and Heijnen [2008] | N/A | N/A |
| CP -/= | N/A | Hach and Spinler [2016] Bajo-Buenestado [2017] | de Vries and Heijnen [2008] Bajo-Buenestado [2017] | de Vries and Heijnen [2008] Assili et al. [2008] |
| CM/RO + | de Vries and Heijnen [2008] Kamalinia and Shahidehpour [2010]* Cepeda and Finon [2011] Iychettira et al. [2014] Hary et al. [2016] Hach et al. [2016]* Keles et al. [2016] Höschle et al. [2017] Bhagwat et al. [2017] de Maere et al. [2017] Traber [2017]* Bucksteeg et al. [2019] | de Vries and Heijnen [2008] Cepeda and Finon [2011] Hach et al. [2016]* Keles et al. [2016] Bhagwat et al. [2017] Höschle et al. [2017] Bucksteeg et al. [2019] | N/A | N/A |
| CM/RO -/= | Léautier [2016]= Petitet et al. [2017]= de Maere et al. [2017]= | Iychettira et al. [2014] Léautier [2016] Petitet et al. [2017]= Traber [2017]* de Maere et al. [2017] | de Vries and Heijnen [2008] Hach et al. [2016]* Bhagwat et al. [2017] Bucksteeg et al. [2019] | de Vries and Heijnen [2008] Cepeda and Finon [2011] Hary et al. [2016] Bhagwat et al. [2017] |
| CfD + | N/A | N/A | N/A | N/A |
| CfD - | de Maere et al. [2017] | de Maere et al. [2017] | N/A | N/A |
| Total + | 25 | 11 | 0 | 0 |
| Total -/= | 5 | 12 | 9 | 9 |

On bold the desired outcomes

= means no effect or ambiguous (dependant on hypotheses)

Table 2.2: Litterature summary over 19 articles

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Appendices

Appendix C

A taxonomy of empirical studies of CRM performance

C.1 Optimization: Central planner perspective

Bucksteeg et al. [2019] consider a pan-European optimization model where the capacity market is described with an additional constraint where only non-intermittent capacity can provide firm energy. They compare different levels of coordination in the implementation of capacity markets in Europe. They find inefficiencies in the uncoordinated approaches (which is not the interest of the present study). Because their model does not allow for blackouts, the energy-only market remains cheaper in terms of system costs at the cost of higher price volatility. However, when post-processing results to subject the mix to additional uncertainty, the hierarchy is reversed, and the energy-only market ranks last both in terms of LOLP and of system costs¹, clearly dominated by the capacity market in which the capacity requirements are based on a probabilistic risk of blackout.

C.2 Optimization and equilibrium models: Firms' perspective

Driven by the liberalization of power markets, a new range of model paradigm emerged as an alternative to the central planner perspective. Indeed, the introduction of competition shifts the focus from the system as a whole to the agents' preferences. Firm oriented models usually maximize the profits either in pure and perfect competition or in imperfect competition. The latter is especially useful for its ability to represent market power in different forms. This can result in suboptimal equilibrium (Nash equilibrium) that follows from the firms' behavior and market clearing procedure.

Kamalinia and Shahidehpour [2010] consider a real option model where investors consider the trade-off between investing now or later. For the market-clearing, they account for the prevailing power flow constraints (power balance, DC power flow, line flow limits, gen-

¹the post-process values the blackouts.

eration limits, demand range, and the reference bus angle constraint) when maximizing the welfare (the difference between the power demand and supply curves). They compare the energy-only market with Three alternative designs. The Capacity payments are based on LOLP and VoLL, the ICAP design² results of a reserve margin imposed on LSEs (demand) while locational capacity prices (LCP) are based on the marginal cost of capacity (shadow price). Modeling options of the ICAP and LCP seem rather close to a capacity market definition. In a system with low locational constrained, they find the energy-only, CP, and LCP to perform similarly in terms of investment timing and welfare. The system becomes constraint earlier in the ICAP model leading to a strong redistributive effect from consumer surplus to producer surplus in exchange for increased security of supply. When considering a more constraint system, investments occur earlier in the LCP design (before outages) thanks to a market-based approach. Investments are also found more profitable, and market power is reduced (capacity withholding).

Höschle et al. [2017] consider a capacity expansion model (greenfield) in perfect competition with energy, flexibility, emission neutral injection, and availability constraints. Modeled as a non-cooperative game, each price taking agent maximizes its own utility under constraint is given the action of the others: the solution is a Nash equilibrium. They consider an equivalent Mixed Complementarity Problem (MCP) formulation using the first-order optimality conditions that result in hourly energy prices, daily reserve prices, annual capacity and green certificate prices. In this framework, they compare the EOM outcomes with those of a strategic reserve and a capacity market. Per definition, both increase available capacity compared to the EOM. However, the mix is profoundly impacted by the mechanisms. Because they do not effectively account for the interaction between flexibility and availability, targeted mechanisms as strategic reserve produce inefficiencies that do not appear under market-wide mechanisms such as capacity markets. Capacity markets are able to induce a cost-efficient reserve margin while effectively pricing energy, flexibility, and CO₂.

de Maere et al. [2017] considers the effect of incomplete risk trading on investment comparing complete markets with incomplete markets where different kinds of hedging contracts are eventually traded. They use a two-stage stochastic equilibrium model applied to an energy-only market model where price taking risk-averse agents maximize their profit and surplus. In the first stage, investments are decided, and contracts are traded. In the second stage, uncertainty is revealed, the markets are cleared and contract paid. Investment costs, driven by the market risk, are directly affected by the market design. This leads to low investments in the energy-only market without risk trading. However, the introduction of hedging contract such as contract-for-differences (CfD) and reliability option (RO) without physical back up bring the welfare close to the complete market situation. They are efficient in mitigating the market risk but their empirical efficiency remains to be assessed as the liquidity required is far from what is currently observed. RO with physical back up usually leads to over investment compared to the complete market case

²As formerly in PJM, ISO-NE, and NY-ISO.

(EOM with perfect hedging), while without physical back up, under-investment can occur under certain circumstances: results in terms of security of supply are ambiguous. Similarly, CfDs performance is subject to market liquidity. The implementation of a forward capacity market also effectively reduces the hurdle rate, but its cost efficiency is subject to the optimality of the target³.

Traber [2017] computes a Partial equilibrium model (mixed complementarity problem) where the capacity constraint drives investment in a perfect foresight environment. They take the energy-only markets as a reference and compare its outcome with different CRM designs: a strategic reserve, a capacity market, and reserve obligations⁴ that we will disregard. Because of the perfect foresight assumption, the EOM always leads to lower end-user prices, higher welfare, and higher consumer surplus. The introduction of CRMs reduce the variable costs of generation and increase the generators' revenues. They conclude that the long term welfare effect of each kind of CRM depends on the structure of the market. This could turn out to be a problem given the current pace of change in power systems.

In Hach and Spinler [2016], the focus is on the gas turbine investors' decision in a context of stochastic electricity and gas prices modeled through a geometric Brownian motion. Investors can either decide to invest immediately or later based on their profit expectations. Capacity payments are represented as exogenously determined revenues varying from 0 to 50 000€/MW/year. In line with utilities' claims, they find investments in CCGT⁵ to be unlikely in the European context. Investments are conditional to both load factors and level of payments. The lower the load factors, the higher the marginal impact of capacity payments. They conclude that capacity payments could be an effective tool to compensate for the low load factors induced by renewable integration.

C.3 Simulation: agent-based

Agent-based models focus on agents behavior: they make their decisions based on behavioral rules and learning from past experiences.

Keles et al. [2016] investigate how SR and CM guarantee the security of supply under high renewable penetration. The agents get the opportunity to invest in a random order, only in a technology they already own. They make their decision with bounded rationality in the technology with the highest NPV (when positive). The SR secures a reserve margin of 5% of peak load, with prices capped at the cost of new entry. When contracted, plants can never participate in the energy market; they are only dispatched by the TSO and receive compensation for their variable costs. The capacity market is a centralized forward one in which the regulator determines the target capacity, and each LSE secures an amount corresponding to their peak demand. Generators bid their profitability gap. Benefiting

³Again, the outcomes are ambiguous as they depend on the parameters, especially the level of the target compared to the peak demand. Only a target superior to peak demand ensures the security of supply.

⁴suppliers have to buy capacity certificates to cover their peak demand.

⁵combined cycle gas turbine.

from the current overcapacity, the reserve margin is limited but sufficient in the EOM. However, system security is at risk in the long run. When a strategic reserve is added, capacity is shifted 5% up, and reliability is partially restored. The existence of a capacity market generates even higher investments without increasing the system costs thanks to avoided scarcity. This, however, is sensitive to CM parameter.

To assess the question of asymmetric CRM implementation with high renewable penetration, Iychettira et al. [2014] run an agent-based model under demand and fuel price uncertainty. The renewable target is independent of the budget constraint. The capacity market is modeled with a sloped demand curve where generators bid the marginal cost of capacity (profitability gap). In this framework, the supply ratio is improved, and energy prices reduce. The counterpart for lower outages is the increase in consumer bills due to the capacity cost component.

In Genoese et al. [2012], generators have to invest in maintaining their portfolio. They will invest in the technology with the highest NPV. Capacity payments are granted to new plants and refurbished units given the reserve margin at the time of investment is low: the lower the reserve margin, the higher the payment. Compared to the EOM, more capacity comes online under CP, the effect on electricity prices is negligible.

Bhagwat et al. [2017] investigate the efficiency of CM and SR in interconnected markets. In the CM, a sloping demand curve is confronted with plants bidding their missing money. The SR contracts power plants that get their fixed operation and maintenance costs paid. Once contracted, plants can only bid into the energy market at a predefined high price. The two CRMs improve the security of supply and reduce consumer costs.

Bhagwat et al. [2016] considers the effectiveness of an SR under high renewable in-feed thanks to an agent-based model. The market outcomes of a baseline (no SR) are compared with those under SR under uncertain demand growth and fuel prices. Those two are then confronted with a situation with high renewable. The plants with the highest variable costs are contracted in the reserve (lowest opportunity cost of exiting the market) up to a fraction of the total peak load. They are provided with full costs recovery and generate when a price reaches a given strike price (set so the SR does not affect the revenues of the remaining plants). Electricity prices are more stable under strategic reserves while SoS is improved, investment cycles are reduced but still occur.

C.4 Simulation: system dynamics

System dynamics models highlight state changes instead of seeking the optimal solution. In this paradigm, the path towards the solution is of interest, and feedback effect is allowed.

By use of a dynamic capacity investment model⁶, Hach et al. [2016] build a capacity

⁶The model used is non-consensual in the literature: although Bublitz et al. [2019] consider the model type to be "single firm optimization", Bhagwat et al. [2017] considers it as system dynamic while Höschle et al. [2017]

auction where generators (existing and new) bid their profitability gap. The electricity market clearing includes strategic behavior (plants bid above marginal cost, as a function of the reserve margin. "Individual profit-maximizing investors who require expected profitability of all existing generation and new projects". They distinguish the case where only new capacity can take part in the auction to the market-wide auction. In any case, new plants are receiving the capacity price for ten years, and units that do not clear are not invested in (eventually decommissioned). The introduction of a CM is found positive, even accounting for strategic behavior. It decreases and stabilizes prices while increasing reliability: the cost of capacity does not outweigh the reliability gains⁷. Besides, sustainability is unaffected because the new investments are less CO₂ intensive than the existing.

Assili et al. [2008] consider a perfect competition framework modeled with system dynamics to set out the trajectory towards equilibrium conditions. To meet the targeted reserve margin of 10%, a capacity payment, and variable capacity payment are modeled. The capacity payments consist of a technology-specific share of investment costs, which is decided annually. The variable capacity payments differ in that the share varies depending on the need for capacity and only benefit to combined cycle gas turbines (CCGT), which is considered as the most needed technology. Both improve reliability and reduce system costs as well as investment cycles.

de Vries and Heijnen [2008] investigate investment under demand uncertainty. They model different market designs in a context where firms have market power. They maximize their profit and reinvest at least part of their revenue. In the EOM configuration, investments are only driven by energy prices. The capacity payment is set exogenously and adds up to generators' revenues. The operating reserves are procured on a daily basis (10% of peak demand). In the obligation framework, each LSE needs to procure a capacity margin of 10% over its peak or face a penalty (soft constraint). The EOM is characterized by investment cycles and a high standard deviation of shortages. Those are reduced if an oligopoly can raise prices by 10%. The increased reserve margin stabilizes prices and investments. Consequently, all CRMs perform better than the EOM in CPP in terms of price levels and shortages. Investment cycles are also lower. When advocating for the best design, they argue that the obligation should be preferred in the sense that it mitigates market power and ensures a cost-efficient security of supply.

Cepeda and Finon [2011] investigate how interconnected markets react under different configurations of EOM, capacity payments, and Forward Capacity Market with a price cap and a penalty. Because the modeling of the CM is close to reliability options, we will use this terminology. As usual, we will abstract from policy coordination problems and only consider the symmetric cases (EOM and RO). RO as call options with a strike price and procured three years ahead. The EOM manages to guarantee the security of supply even in the presence of investment cycles. The implementation of a CRM always leads to

describes Monte Carlo Simulations.

⁷The VoLL is set at 10000 pounds per MWh.

higher prices due to the capacity cost component. The RO provides effective investment incentives (no investment cycle) through reduced price volatility and little scarcity.

Petit et al. [2017] tests the relative efficiency of the EOM and the CM when the investors are either risk-neutral or risk-averse. In a myopic foresight, investments are carried out based on a profitability index. The capacity target is for each scenario to meet the reliability target. Generators then bid their missing money on the capacity market. Without risk aversion, the EOM performs well. However, risk aversion impacts the EOM results negatively while the CM remains relatively unaffected. Indeed, risk aversion reduces the reserve margin with lower investments and earlier decommissioning. The LOLE is increased. In a context of high risk-aversion, the welfare is better off with a CM, which is not so obvious in a risk-neutral world.

Hary et al. [2016] discuss peak load coverage and investment cycles when electricity demand is uncertain and inelastic. They consider a four-year forward capacity market and a reserve where the TSO procures the non-profitable plants up to the reserve margin. Both the CM and the reserve increase the reserve margin compared to the EOM. Similarly, the investment cycles are reduced thanks to the SR, but disappear under CM. The CM is more cost-efficient in terms of generation and shortage costs while reducing the probability of shortages.

C.5 Analytical models

Bajo-Buenestado [2017] is interested in price caps and capacity payments under imperfect competition. Capacity payments are endogenously calculated and come as a reduction of the investment cost. In the two-stage model, two types of generators (base or peak) first make their investment decision. Then, they participate in the electricity auction bidding prices and quantities in the second stage. In the EOM, the consumer surplus is increased when price caps are removed. Outage probability is also reduced. However, in the presence of a dominant fringe, the removal of price caps increases the market powers at the expense of consumers. This is, without lowering the probability of shortage. The introduction of capacity payments creates a trade-off between lower outage and volatility and affordability. Indeed, capacity payments tend to increase electricity prices. Thus, it reduces both the consumer surplus and increases the reliability compared to an EOM. The efficiency of CP is, however reduced with strategic actors.

In a two-stage Cournot game, Léautier [2016] investigates under-investment. Given an elastic enough demand, the price cap is never binding in perfect competition. However, as soon as market power arises, he finds that underinvestment becomes structural. It is driven by the strategic behavior of market participants while the price cap becomes binding. Consequently, he considers different market designs: Hogan's energy operating reserve (ORDC), a decentralized forward market, and financial reliability option with a penalty. With imperfect competition, under-investment remains when the ORDC capped at average VoLL is implemented: the situation is similar to the EOM. With respect to

the capacity market, investment incentive is restored only if the capacity certificates are backed by actual capacity. Generators' profits are increased, and capacity is then optimal, so is the welfare. The reliability options do limit market power, but they effectively restore investment incentives when attached to physical support.

Chapter 3

Information Value in Capacity Market Designs: Public Consultations and Requirements Definition

Co-authored with Morgan Patty

Abstract

In electricity markets, the public authority can design capacity markets (CMs) to bring market outcomes in line with social optimality. By pricing capacity as a separate good from electricity, CMs stabilize and complement the revenues of plants so to generate sufficient security of supply (i.e., having enough capacity available to avoid rationing) at potentially lower cost for end consumers.

In decentralized forward capacity markets, information about likely capacity requirements is a crucial issue. The –welfare optimizing– public authority thus decides whether to make this information binding (*ex ante* requirements as in the PJM capacity market design of 1999) or to base capacity demand on realized market outcomes (*ex post* requirements as in the current French CM design). Adapting a Cournot oligopoly model from Roy et al. [2019], we analyze a capacity market where homogeneous buyers aim to comply with their capacity obligation under uncertainty regarding future realized demand. We thus consider a Cournot oligopsony in which the capacity buyers (mainly load-serving entities) are profit-maximizing agents engaging in strategic behavior. Heterogeneous capacity owners bid their valuation of capacity. As information disclosure reduces uncertainty on the one hand, but may also decrease precautionary capacity buying by load-serving entities on the other, we seek the preferred level of information precision, i.e., *ex ante* or *ex post* disclosure of capacity requirements. Counter-intuitively, the welfare-maximizing level can be lower than full precision of information. The model also highlights possible disagreements between capacity buyers and capacity owners, considering that dissemination of public information might affect their surpluses in different ways. In addition,

when public consultations are organized, capacity owners are able to individually express their preferences. This may lead to divergence between the result of majority voting and aggregated profit maximization as not all agents are uniformly affected by different modes of disclosure. The particular case where the public authority chooses majority-voting as a decision rule is investigated in detail. Using German data from 2010, model parameters are set to mimic several plausible capacity market designs. Results suggest that *ex ante* requirements are empirically likely to be favored.

3.1 Introduction

The features which make electricity so peculiar compared to other goods are the non-storability combined with demand inelasticity. Indeed, no economically viable solution has yet emerged to store electricity on a large scale. It follows that demand and supply require a continuous balance to avoid system failure (black-outs). Unfortunately, this task is impaired by the low predictability of demand. End consumers are rarely informed of the state of the wholesale market and thus do not receive any kind of price or scarcity signal to adjust their consumption to real-time conditions¹. In this framework, the peak demand is binding, and available capacity units play a crucial role in keeping the system up and running. In a free market, this means that those units need full cost recovery - at least in expectations. If not, adequacy² problems appear. Indeed, the Security of Supply (SoS) is supposedly a byproduct of the energy market, but some stakeholders cast doubt on the capacity of an energy-only remuneration to ensure a rate of return high enough to trigger investments. Observers even mention plants being unable to cover their fixed costs through the energy market [Joskow, 2006; Cramton and Stoft, 2006]. Such early retirements could endanger the system stability. In that case, the most mainstream option to make sure enough capacity will be available is to implement a capacity market as a complement to the energy market –other designs exist but are not considered in this chapter.

In reality, consumers have little incentive (or way for that matter) to disclose their willingness to pay for SoS, mainly due to the non-excludability of SoS³. Therefore, they cannot be discriminated against their willingness to pay for reliability. Their theoretical willingness to pay for the SoS is thus estimated by the Value of Lost Load (VoLL)⁴. They are

¹See Joskow and Tirole [2006] for a discussion about the causes of end consumers' inelasticity.

²NERC [2017] defines adequacy as "the ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements". We will alternatively use the Security of supply (SoS) and Reliability for similar meaning.

³Imbalance between supply and demand can provoke system failure and rationing independently of individual preferences. Electricity rationing is seen here as the unplanned forced reduction of consumption.

⁴The Value of Lost Load is defined as the average value placed by end consumers on losing power in an average rolling blackout by Cramton et al. [2013]. Besides, it should be noted that the VoLL is challenging to estimate and probably non-linear as well. Security of supply is also valued at the margin by the cost of new capacity. At equilibrium, willingness to pay for additional capacity and cost of new capacity are equal.

commonly assumed to be willing to avoid black-outs in an equal manner, and retailers are enjoined to get enough capacity to cover their aggregated peak demands on behalf of their portfolios. The underlying reasoning is the following: the level of available capacity has to surpass demand at any point in time to avoid rationing. This implies that a piece of SoS is embedded in each capacity unit.

Thus, capacity markets standardize capacity with respect to the SoS through the notion of "firm capacity"⁵ and then pay units for their insurance value (against black-out). This involves a structural change in remuneration compared to Energy Only Markets (EOM). Instead of solely depending on the volatile hourly energy prices, capacity owners⁶ can additionally benefit from a (yearly⁷) fixed remuneration contingent on the size of their unit. This covers at least part of the fixed costs, reducing the risk associated with the participation in the energy market, simultaneously decreasing the required return on investment. The cost incurred by the contractual obligations such as availability and outage management should remain low because they are already incentivized by the normal functioning of the energy market [Stoft, 2002]. Thus, the capacity remuneration is often seen as a complement to the energy revenues. Without strategic bidding, capacity owners should be willing to recover at least their participation constraint to the energy market (b_i) being $b_i = \max(-\mathbb{E}(\pi_i); 0)$. It is, however, complicated to know whether capacity owners actually bid their competitive price on the capacity market⁸. Even if they do so, the participation constraint highly depends on each owner's expectations, costs, as well as the cost of meeting the contractual requirements. In real-world conditions, the very sensitive nature of the information embedded in each bid causes the order book to remain undisclosed or anonymous. This chapter will thus empirically focus on competitive bidding from the capacity owners, although the theoretical model allows for a wider variety of strategies.

Under capacity remuneration, the demand-side (mainly load-serving entities - LSEs)⁹ benefits from additional SoS and, the supply-side gets extra revenues. This is Pareto-improving as long as the marginal cost of procurement (cost of the marginal unit) is lower than the marginal cost of a black-out. In this sense, capacity markets may make both kinds of actors better off, but the market design affects them in different ways. More specifically, this analysis focuses on decentralized capacity markets.

Where most existing capacity markets centrally procure capacity on behalf of the LSEs (or end consumers) who pay for their own market share –e.g., the United Kingdom (the UK) or

⁵Firm capacity is the share of the installed capacity that is expected to be available at peak.

⁶Capacity owners are generally, but not limited to, the electricity generators.

⁷Most common current capacity contract length for existing capacity.

⁸Indeed, great attention is granted to market power mitigation in all existing capacity markets: according to Teirlä [2017], current strategies are quite effective.

⁹Load Serving Entities (LSEs) are generally the electricity retailers that supply the end consumers. More formally, according to NERC [2017], an LSE is an entity that "secures energy and Transmission Service (and related Interconnected Operations Services) to serve the electrical demand and energy requirements of its end-use customers".

the Eastern US systems—, decentralized capacity markets shift this burden directly on the LSEs – e.g. France or former MISO¹⁰–. As recent designs tend to procure capacity several years ahead, the definition of capacity requirements becomes a key feature of decentralized capacity markets. Again, two types arise: (i) *ex ante* requirements are determined by the system operator¹¹ and announced in advance to obliged parties (LSEs). This leaves no uncertainty for them (former MISO, former PJM), except maybe if their market shares change. In (ii) *ex post* requirements, the obligation depends directly on the realized market conditions (France). Therefore, LSEs do not know the exact amount they should buy at the moment the auction takes place: there is uncertainty not only on their market shares but also on total volume to be acquired. If their level of procurement is not sufficient, they may be penalized by the public authority for having endangered the SoS (i.e. their peak demand has surpassed the amount of their capacity certificates). This leaves a high uncertainty. Table 3.1 presents empirical examples of existing and past capacity market designs with respect to the two features discussed above. For clarifications, chapter J provides a thorough discussion on design-related information precision and discusses the demand-side specification in the respective capacity markets of the UK and France. This chapter focuses on actors’ preferences with respect to this last design feature: requirement definition.

| | | Requirement | |
|------------------|---------------|--|----------------|
| | | <i>ex ante</i> | <i>ex post</i> |
| Market Structure | Centralized | UK (2017) | - |
| | Decentralized | Former MISO (2009), Former PJM (1999) | France (2017) |

Table 3.1: Market Structures and Requirements in CRMs

An institutional perspective on market-based CRMs illustrates the key role of uncertainty in CRM designs over time. Along with the SoS objective, CRMs seek to replace scarcity pricing¹² when deemed inefficient. This is why the first CRMs were implemented on a short term basis in the 1990s. In the England and Wales Pool, the payments resulted from an *ex post* settlement based on the energy market clearing (half-hourly)¹³. In the PJM¹⁴, the LSEs were obliged to secure their share of total capacity obligation on a daily basis. Both types of markets (price-based and quantity-based) ended up with the same flaws: high price volatility and confirmed market power expression. All short-term

¹⁰MISO (Midcontinent Independent System Operator) has a broad footprint that spreads from Canadian provinces to southern US states such as Mississippi and Louisiana.

¹¹The system operator is the public structure in charge of the operability and the distribution of electricity.

¹²Cramton et al. [2013] explain that scarcity periods are, in fact, market failures and prices during these periods do not represent the meeting of supply and demand.

¹³Refer to Newbery [1998] for further details on the England and Wales Pool

¹⁴PJM (Pennsylvania, New Jersey, Maryland) ran a decentralized capacity market. Refer to Bowring [2008] for further details on the former PJM capacity market.

mechanisms were abandoned by the end of 2000s to the profit of extended contract periods and forward procurement of capacity (PJM, ISO-NE, Colombia and later the UK). Both changes aimed to reduce the uncertainty on the capacity market outcomes, but also on the level of SoS achieved. The increased predictability of future profits was supposed to improve the investment climate as well. On the demand-side, the shift of decentralised markets to central procurement lowered more the risk borne by the LSEs as the main cost of capacity would be known 3 to 4 years ahead. Only the split of such costs between LSEs would keep a slight uncertainty for being based on their market shares at peak. Until recently, the LSEs did not seem to be given an active role in capacity markets: even decentralized markets such as the former PJM centrally determined the amount of capacity to be procured¹⁵. LSEs' liability was restricted to their market share irrespective of the actual Loss of Load Probability (LoLP)¹⁶ achieved. The situation in MISO (2009-2012) corresponded to a slightly different liability: LSEs did self-estimate their peak demands, but as long as their good faith was not questioned *ex ante*, they did not face penalties even if their forecasts were proven wrong *ex post*¹⁷. In this sense, the choices made in France, with a decentralized market and *ex post* requirement settlement raise questions around the role of the risk borne by LSEs. While *ex ante* requirements have historically dominated implemented designs, the technical and economic improvements of Demand Response (DR) give an opportunity for *ex post* requirements to demonstrate their advantages. Indeed, in a decentralized CRM combined with *ex post* requirements, LSEs have to procure capacity based on their realized peak demand (which implies that no explicit capacity target is set). This is claimed to reduce over procurement [RTE, 2014] but also to foster DR, which is becoming an essential SoS levy. The main difference with the previously described regulations (former PJM and MISO) is that the accuracy of LSEs' prediction matters since they fully benefit from their decisions¹⁸.

The importance of transparency is illustrated by continuous discussions about the level of available information, raising concerns on the best information structure. For instance, the European Federation for Energy Trading (EFET) advocates for more transparency of the French mechanism [EFET, 2016], meaning that a remaining margin for additional information disclosure has been identified. Elseways, the market monitoring of ISO-NE¹⁹ has been advising for reduced transparency under the belief that it increases the market power of the supply-side [Patton et al., 2017]. This chapter focuses on the informational value of peak demand forecasts for capacity procurement in decentralized capacity markets. To the best of our knowledge, it is the first study isolating the effect of requirements in capacity markets with the buyers' side taken as the strategic side. We ask questions about the actors' preferences in terms of design, focusing on the uncertainty aspect of the

¹⁵Each LSE had to procure its share of the centrally forecasted peak demand [Bowring, 2008].

¹⁶The LoLP measures the probability that demand out passes supply.

¹⁷As long as the error ranged within acceptable boundaries specific to the methodology used.

¹⁸When the capacity cost is dealt depending on LSEs market share at peak (and not realized demand at peak), the individual actions of the LSEs are diluted which is more prone to free-riding.

¹⁹ISO-NE: Independent System Operator of New England.

problem, and, letting the market organization for further research.

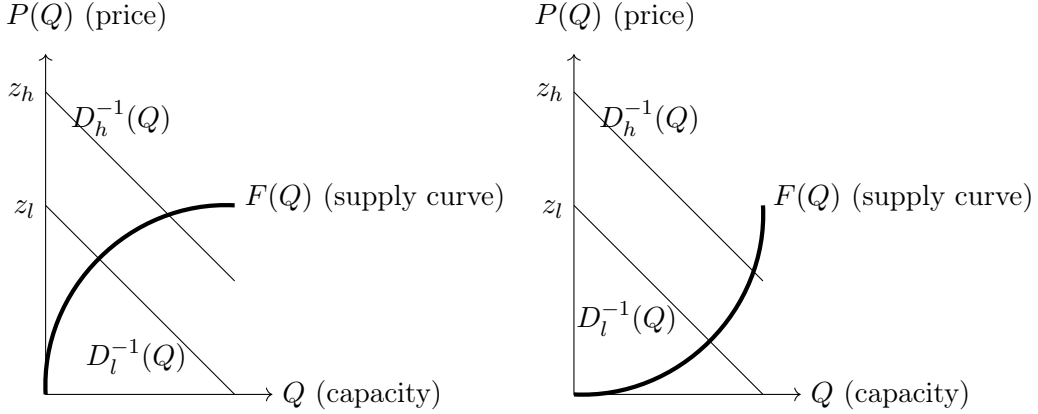


Figure 3.1: Graphical example - Uncertain linear marginal value curve with two possible states h and l (two possible intercepts z_h and z_l), and a concave supply curve (left) or a convex supply curve (right)

The chapter is organized as follow: section 3.2 establishes a brief literature review. Section 3.3 develops the theoretical model used to analyze the preferences in terms of information precision in capacity markets. We adapt the Cournot oligopoly model of Roy et al. [2019] to a Cournot oligopsony²⁰ under the hypothesis of non-atomicity on the supply-side, i.e. all capacity owners are small agents, and capacity owners have heterogeneous valuations of their good. On the demand-side, homogeneous LSEs have linear marginal values²¹ (see Figure 3.1). We assume there are two states of the world, in which the level of the capacity buyers' marginal value differs (see Figure 3.1). The public authority can reduce the uncertainty about the state of the world, by making the signal binding: with *ex ante* requirements, the capacity buyers are unaffected by the uncertainty around the states of the world. Indeed, the signal indicates to the capacity buyers what is their true marginal value. Precision is the key element of the design: increased precision reduces the uncertainty on the requirements (see chapter J for the link between demand uncertainty and capacity requirements). Thus, it impacts the quantities and the price of capacity units traded in the market by affecting the beliefs of the capacity buyers (their posterior). Results show that preferences about information disclosure depend on the shape of the supply and marginal value curves and that they may diverge among market participants. In a context where the public authority does not perfectly know the surpluses, it resorts to a public consultation to aggregate the expressed preferences following its objective function.

The public authority can be mistaken by collecting preferences if she uses the majority-

²⁰An oligopsony is equivalent to an oligopoly where buyers represent the strategic side.

²¹The marginal value is analogous to the marginal cost for an oligopsony i.e., it is the willingness to pay an additional unity for the good (capacity unit). In oligopsonies, the price is lower than the marginal value for a given quantity, since the buyers can exert market power.

winning criterion as a proxy for the profit-maximizing one. When capacity owners are heterogeneous, the majority-winning criterion can differ from the profit-maximizing one. However, section 3.4 shows that this situation is empirically unlikely to occur. Indeed, the fourth section illustrates the implications through a case study. The model is parametrized according to the former German situation (2010) as well as possible capacity market designs. In this case, disagreement between the majority-winning criterion and the profit-maximizing one is quite unlikely. Indeed, it only appears locally when the shape of the supply curve (all other things being equal) changes such that a lower information precision starts being preferred by capacity owners: it only represents a transition where the preference of the majority changes before the profit-maximizing one. Similarly, extrapolating the case study results to real-life situations indicates that reduced information precision would not be welfare-maximizing in an adequate market. However, the need for new entrants, who bid significantly higher than existing units, might generate such a situation. The last section concludes the analysis.

As simplifications are inherent to modeling, we do not consider some important elements of the design. For example, the timing aspects of a capacity market do not enter in the framework of our static model. For instance, a more complete setting may be needed when considering questions about the degree of forwardness and contract duration. Besides, performance obligation and assessment or even the market eligibility of different technologies are considered to be directly accounted for in the bidding behavior of the capacity owners: the supply-side behavior is only restricted by the hypothesis of continuity. Similarly, all SoS considerations (cost of black-out, VoLL etc.) are implicitly embedded in the model parameters and thus little discussed.

All in all, we use a simple oligopsony model to investigate the design process of CRMs and the informativeness of public consultations for the public authority. We focus on decentralized capacity markets and investigate the actors' preferences with respect to requirement definitions as if it was the only design question left unanswered. Alternative forms of CRMs are disregarded.

3.2 Literature Review

3.2.1 Electricity markets: Relevant literature

As discussed in section 3.1, potential market failures endangering SoS have been identified and thoroughly discussed in the literature for some time. A good synthesis of the discussion can be found in Cramton et al. [2013]. While the usual taxonomy does discriminate for the degree of centralization [Henriot and Glachant, 2013; Meulman and Méray, 2012], the timing of requirement assessment (*ex ante* vs. *ex post*) is often blended in the definition. Indeed, Woodhouse [2016] rightfully argues that decentralized CRMs reduce the risk of over procurement and generate a more flexible framework for new SoS products. In this discussion, it is, however, implicitly assumed that *ex post* requirements are

inherent to decentralization. In turn, Parsons and De Sisternes [2016] note that uncertainty about extreme events (which are hard to apprehend since they are rare) leads to *ex ante* disagreements between LSEs and generators. Naturally, *ex post* disagreements about the underlying causes of scarcity during these events subsist. Therefore, conflicts emerge about the responsibilities of each actor during rare events. Finally, the question of the optimal level of SoS is left unsolved. However, when designing a CRM, the public authority brings out the debate, and forces market actors to solve this conflict *ex ante*, justifying the existence of the CRM. Parsons and De Sisternes [2016] conclude that a CRM should help reducing the *ex ante* uncertainty. Through this channel, the risk is reduced for both LSEs and generators. The link with *ex ante* requirements is obvious: actors settle their disagreement on the SoS and agree on a given level of capacity. With respect to *ex post* requirements, CRMs leave part of the disagreement unsettled because they only set the liabilities, not firm objectives.

A broad strand of theoretical literature investigates the relationship between the optimal level of SoS and demand characteristics (uncertainty, elasticity). It reveals that full demand coverage is socially inefficient. For instance, Chao [1983] considers an electricity market under supply and demand uncertainties. The stochastic demand leads the utility (the vertically integrated electricity supplier) to adopt a technology mix to minimize its costs. Then, the paper establishes an optimal capacity structure and discusses reliability criteria, giving the best level of SoS from a welfare point of view. In the case of a convex outage cost²², the optimal mix depends naturally on the probability and the expected amplitude of a blackout (demand-side), and the cost and the availability of each technology (supply-side). Chao and Wilson [1987] are interested in how the SoS can be ensured by reducing the end demand during scarcity periods. For this purpose, they set a similar framework, but they add priority service (i.e. the fact to discriminate end consumers, by selling different levels of reliability to the different types of end consumers who self-select with menus). Priority service transmits information about the distribution of the willingness to pay to the utility. Therefore, the optimal level of capacity can be measured directly with the optimal priority charges. They show that reducing the demand of the less willing to pay end consumers in times of scarcity and spot prices are equivalent from an optimality point of view. Chao et al. [1988] look at the market structure impact on surpluses. They note that most of the efficiency gains are realized with few priority service classes (i.e. end consumers are pooled in two or three categories), end consumer surplus and welfare then keeping on increasing with the number of classes.

The role of consumption choices (consumption patterns) in the SoS problem has thus long been identified. The literature also highlights the optimality of respecting demand-side preferences in terms of reliability. However, the proposed solutions to approach optimality have long been little applicable in reality. Only recent technical evolutions (smart meters) open the way for accurate market segmentation based on reliability preferences. In the meanwhile, public authorities often exogenously set a reliability target as a proxy for the

²²Outage cost is the sum of the rationing cost and the foregone consumers' surplus.

optimal level of SoS, which can be further enforced via a CRM. The motivations and consequences of such a choice have been investigated in the literature.

In the same strand of the literature, Joskow and Tirole [2006, 2007] set a more realistic framework with price-insensitive and price-sensitive end consumers. Interested in retailers' behaviors, Joskow and Tirole [2006] study the competition between LSEs for end consumers. Assuming competitive markets, they focus on potential suboptimality because of information withholding about the profile of end consumers (due to the presence of several LSEs). With this paper, they open interesting debates on the regulation of the LSEs and the demand of end consumers that are still unsolved. Expanding this analysis in Joskow and Tirole [2007], they study the effect of the price cap and capacity payment together. They argue that setting a price cap is useful to decrease the market power of the supply-side but creates a missing money problem. In line with Chao and Wilson [1987], Joskow and Tirole [2007] find that rationing price-insensitive consumers may be optimal. The authors show that the Ramsay optimum may be attained with capacity payments when all consumers pay for capacity. However, the market power of the supply-side in the electricity market can undermine this result.

Considering two interconnected areas, Crampes and Salant [2018] investigate the social gains from trading between the two regions and further regard the case of capacity credits. They assume that only a reduction in the occurrence probability of blackouts matters in the optimal capacity programs resolution (and that is why some plants are only built to deal with capacity problems). Crampes and Salant [2018] explain that financial incentives for peak supply or installed capacity may generally solve missing money problems.

As highlighted in the aforementioned papers, the elasticity of the demand for electricity plays a key role in determining the optimal level of SoS. The increasing technical and economic feasibility of Demand Response (DR) asserts voluntary rationing as a levy towards a better understanding of end consumers' preferences with respect to SoS and increased demand elasticity. For instance, Lambin [2018] analyses the effects of heterogeneous DR units (ordered with respect to the opportunity cost) on an electricity market with a price cap. DR units ranged below, and above the price cap are found to have distinct effects. Then, an optimal payment structure for DR units in a CRM can be derived, where distinct payments are recommended: DR units below the price cap should receive a more advantageous remuneration.

Finally, the complementarities of the electricity and capacity markets are repeatedly highlighted by different stakeholders either to discuss the need for CRM or even to caution against the risk of complex strategic behavior. This is why scholarship often analyses capacity markets jointly with electricity markets [Joskow and Tirole, 2007; Teirilä, 2017; Astier and Lambin, 2019]. A step further, Teirilä [2017] specifically focuses on the bidding strategies that can emerge in both markets when capacity owners acknowledge the complementarities between them. The present analysis will, however, consider the capacity market in isolation from the electricity market to favor intuition. Some strategic

interactions between the two markets are implicitly accounted for thanks to the reduced assumptions on the bidding behavior of the supply-side.

While CRMs are broadly discussed in the literature, decentralized capacity markets have received limited attention, although the strategic dynamics might significantly differ. The uncertainty on capacity requirements is often discussed, but rarely investigated because most CRMs rely on *ex ante* requirements. In the continuity of this literature, we specifically focus on requirements uncertainty. With the implementation of *ex post* requirements, the risk associated with the peak consumption unpredictability is partially shifted onto the demand-side. In a context where capacity markets may be increasingly decentralized in the near future to further involve the demand-side (and other new products) [Woodhouse, 2016], the question of design-related risk shifting and actors preferences with this respect deserves reflection.

3.2.2 An adaptation of Roy et al. [2019]

The majority-winning procedure used in Roy et al. [2019] is an interesting way to materialize the discussions between market participants and the public authority about the design-related information precision (*ex ante* or *ex post* requirements). Indeed, in the context of implementing a brand new capacity market or redesigning one, having a view on the interests of the different stakeholders is essential. Both groups, LSEs, and generators, are usually consulted in the process and are probably to defend their own interest rather than the welfare-maximizing design. In the electricity sector, the heterogeneity of production technologies makes the discussion on the individual preferences of capacity owners highly relevant. Thus, only looking at the profit-maximizing design may not be sufficient to fully understand the preferences of the capacity owners. On the contrary, retailers can be seen rather homogeneous actors competing on quantity in a (decentralized) capacity market.

To match our interest in the demand-side strategic behavior under uncertainty and actors' preferences in terms of information, we adapt an existing model from Roy et al. [2019]. They are interested in the preferred information disclosure when homogeneous producers competing *à la Cournot* face uncertainty about the state of the world (their constant marginal cost can take two equiprobable values, high or low). The non-linear demand is made of a continuum of heterogeneous consumers with different willingnesses to pay. An omniscient central authority sends a public signal (with value high or low) on this marginal cost with perfect or imperfect precision. Perfect precision means that producers are certain that the marginal cost is the one that the signal indicates. Consumers' and producers' preference about the precision of the signal is characterized by the shape of the demand curve. The notion of majority-winning precision is introduced in this context, and represents the precision preferred by most of the consumers, in contrast to the surplus, which is the traditional criterion. Majority-winning notion enables the authors to show under which conditions there is a disagreement amongst consumers and gives a way to

select the best precision when consumers are considered. Consumers can be divided into three groups: (a) the ones who will always consume (because their willingness to pay is high enough)²³, (b) the ones who may consume, according to the level of production (because their willingness to pay is intermediary), (c) the ones who will never consume (because their willingness to pay is too low). Consumers in group (a) are only concerned by the effect of precision on the mean price of the good (the utility being higher if the price is lower). On the contrary, consumers in group (b) are also affected by the fact that they may *not* consume the good if the level of production is too low. Therefore, a disagreement between consumers may appear if the precision minimizing the mean price reduces the ability to consume for the group (b). On the other side, precision may be detrimental to producers when the competition effect (i.e. the effect of information used by competitors on profit) is too high with respect to the alignment effect (i.e. the effect of knowing better the state of the world on the profit).

In this chapter, we try to understand the consequences of the various designs by investigating how different groups of interest might benefit from one or the other structure of information. Adapting the model from Roy et al. [2019], we explore the preferences of each actor in terms of design in a framework of Cournot competition and uncertainty on the level of demand with varying numbers of LSEs. We generalize the approach of Roy et al. [2019] by considering that the *ex ante* probability of the states of the world can take any value. Considering an oligopsony, our marginal value (the equivalent of the marginal cost) is sloped, enabling the demand-side parametrization to influence the results.

3.3 Model

3.3.1 Description of the model

We adapt the model from Roy et al. [2019] to CRMs, by switching the role of buyers and sellers, buyers becoming the strategic side:

The game is composed of:

- Two States of the World (SoW) $\in \{l, h\}$ affecting the buyers' side, changing the value of: $Z \in \{z_l, z_h\}$, with $z_l < z_h$, and we note μ_0 the common prior belief about the value of $\mathbb{P}(Z = z_h)$;
- n homogeneous buyers, giving the aggregated state-contingent marginal value: $D_{SoW}^{-1}(Q) = z_{SoW} - aQ$;
- Heterogeneous owners, each owner i bidding its capacity unit^a at level b_i , giving the following continuous increasing price function: $F(k) = b_k$;

²³In Roy et al. [2019], the equilibrium is unique for each level of precision. Thus, the minimal and maximal levels of production are known and allow to define these three groups.

- A signal about Z , sent by the public authority, observed by all the buyers: $S \in \{s_l, s_h\}$, of precision $\lambda \in [\frac{1}{2}, 1]$. The signal formed by the authority is correct with probability λ , i.e.: $\mathbb{P}(Z = z_{SoW} \cap S = s_{SoW}) = \lambda \mathbb{P}(Z = z_{SoW})$.
- We note $\mu_h(S) = \mathbb{P}(Z = z_h | S)$, the posterior belief after receiving a signal.

^aThe size of the unit can be considered as small enough to give a continuous approximation. For instance, Joskow and Tirole [2007] considers the supply-side of plants' building as "a continuum of investment opportunities".

Thus, $\mathbb{P}(z_h \cap s_h) = \lambda \mu_0$ and $\mathbb{P}(z_h \cap s_l) = (1 - \lambda) \mu_0$.

Consequently, the buyers have the following beliefs when the signal is high or low:

$$\mu_h(s_h) = \mathbb{P}(z_h | s_h) = \frac{\lambda \mu_0}{\lambda \mu_0 + (1 - \lambda)(1 - \mu_0)}, \quad \mu_h(s_l) = \mathbb{P}(z_h | s_l) = \frac{(1 - \lambda) \mu_0}{(1 - \lambda) \mu_0 + \lambda(1 - \mu_0)}$$

Thus, the buyers have the following conditional expectations about Z :

$$\begin{aligned} \forall \lambda, \quad \mathbb{E}(Z | s_h; \lambda) &= \mu_h(s_h) z_h + (1 - \mu_h(s_h)) z_l \\ &\geq \mathbb{E}(Z | s_l; \lambda) = \mu_h(s_l) z_h + (1 - \mu_h(s_l)) z_l \end{aligned}$$

| signal preciseness | expected state of the world | requirements |
|-----------------------------|--|---|
| $\lambda = 1$ | z_h if s_h z_l if s_l | Fully regulated <i>ex ante</i> requirements |
| $1 > \lambda > \frac{1}{2}$ | $z_h > \mathbb{E}(Z s_h; \lambda) > z_l$ if s_h $z_h > \mathbb{E}(Z s_l; \lambda) > z_l$ if s_l | Partial hedging |
| $\lambda = \frac{1}{2}$ | $\mu_0 z_h + (1 - \mu_0) z_l$ in any case | <i>ex post</i> requirements without hedging |

Table 3.2: How requirements are stylized in the model

Table 3.2 interprets the precision of the signal as the type of requirement in place in CRMs. In the case of *ex ante* requirements definition, λ naturally equals one as the forecast is fully informative (binding): if the central authority indicates that the state of the world will be high, then the buyers know they do have to procure accordingly. With *ex post* requirements definition, however, the signal precision is reduced. Even though the central authority expects the state of the world to be high, it can still be wrong with probability $1 - \lambda$.

Preferences

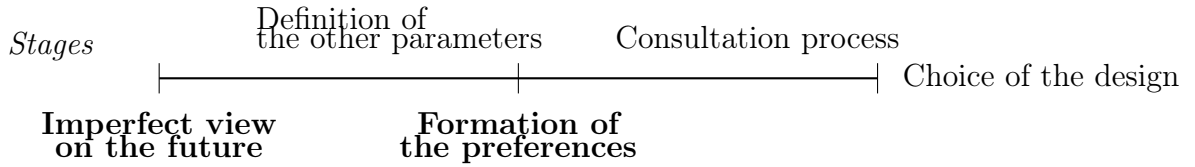
The public authority can stand on the four following criteria to select the precision: either maximize the buyers' surplus, or maximize the owners' profit, or maximize the sum of them, or follow a separate objective function:

- Buyers' surplus: $\max_{\lambda} S(Q) = \max_{\lambda} \int_0^Q D^{-1}(x) - F(Q) \, dx$.

- Owners' surplus: $\max_{\lambda} \Pi(Q) = \max_{\lambda} \int_0^Q F(Q) - F(x) \, dx$.
- Welfare: $\max_{\lambda} W(Q) = \max_{\lambda} (S(Q) + \Pi(Q))$.
- An example of public authorities' objective function: the owners' Majority rule.

The solution concept of the game is a Bayesian Cournot equilibrium: after receiving the signal, all the buyers equalize their expected marginal value with their marginal expenditure (see Pindyck and Rubinfeld [2013], pp. 382-4), giving the expected price and quantities at the equilibrium.

In a context of uncertainty with respect to the level of future peak demand of electricity—that conditions the need for capacity—the public authority can design the capacity market so that the capacity buyers face the consequences of their own electricity demand uncertainty (*ex post* requirements $\lambda = \frac{1}{2}$) or make the adequacy forecast binding (*ex ante* requirements $\lambda = 1$). For having a limited knowledge on the market, the public authority seeks to know market actors' preferences in terms of requirements (λ) through a public consultation. To do so, she first defines other features of the capacity market such as the level of non compliance penalty (affecting the slope a of the marginal value), and the two possible states of the world (z_l and z_h) so market actors can built their preferences in terms of requirements. Such preferences are then collected through a public consultation so the final design can be chosen:



In this chapter, we focus on the formation of the preferences and the consultation process, the parameters being given. However, section 3.4 allows to test the influence of the level of the different parameters empirically, and we establish in this section several results about the sensitivity of preferences to the level of parameter a .

3.3.2 Empirical ground and model hypotheses

This section seeks to link the model assumptions to their empirical meaning. The following considerations are not necessary to understand the model resolution and the main results that are developed in the next section. However, they will be useful in understanding the empirical interpretations provided.

In terms of general hypotheses, the good is homogeneous—as in real life—: each unit of certified capacity confers the same amount of SoS. Therefore, all units of capacity are equivalent in the remainder of the chapter. In addition, the market participants are considered as risk-neutral, meaning that they seek to maximize their surpluses on the capacity market. This is a common hypothesis in the literature (see chapter 2). If those

two assumptions are rather standard in this class of models, the remainder of the section will further discuss the advantages and limits of the choices made in terms of hypothesis compared to actual market conditions.

The supply-side is parsimoniously described in the model. Two main simplifications are made: the heterogeneous capacity owners are (i) non-atomic and (ii) unaffected by the signal. They thus bid their valuation of capacity in a continuous supply curve where real-life conditions rather lead to step-wise supply curves in capacity markets due to the lumpiness of power plants. The underlying assumption is that the size of the steps is considered small enough to defend continuous approximation. This approach is discussed by Chao [1983], who mentions that continuity simplifies but also approximates well the discrete analysis of the optimal capacity structure problem. Similarly, Joskow and Tirole [2007]; Crampes and Salant [2018] explicitly consider continuous capacity supply curves. In addition, capacity owners' bids can be strategic to the limit that the strategy does not account for the signal produced by the public authority. Although this already embeds a broad range of market power expressions, it obviously excludes others that are likely to be observed in practice (e.g., pivotal buyers). In sum, the two simplifications reduce the complexity of the resolution without losing too much in accuracy.

The buyers' side is portrayed through a linear and price elastic aggregated marginal value of capacity units. In practice, the marginal value of capacity is effectively considered as decreasing [Cramton and Stoft, 2007] as the probability of shortage decreases with the amount of quantity procured. Empirically, these considerations translate into the construction of centralized demand curves in capacity markets. Although they are often piece-wise linear (kinked)²⁴, assuming on a linear marginal value of capacity in our framework should not affect equilibrium conditions since they are locally defined. The comparison with centralized mechanisms is facilitated by the assumption that capacity buyers are homogeneous. They thus all have the same marginal value, which is a share of the aggregated one. When their number is high enough, perfect competition arises, which should yield similar outcomes (optimality) than a centralized mechanism run by a benevolent central authority. Any reference to centralized mechanisms in the interpretation of results will refer to this parallel.

The constant slope of the marginal value curve a is assumed exogenous and unaffected by the realization of the state of the world. a is the decrease (respectively increase) of the marginal utility an LSE derives from an additional (resp. less) unit of capacity. It thus embeds the opportunity cost of not buying the additional capacity unit. This can include the non-compliance penalty as defined by the regulator (explicit penalty), the cost of voluntary rationing (Demand Response (DR)) or any direct or indirect costs an LSE can suffer from not buying enough capacity. The unitary implicit penalty resulting from

²⁴In systems with a centralized mechanism, the aggregated inverse demand curves are piecewise linear and decreasing on \mathbb{R}_+ . See chapter J for a description of requirements in the UK and France and <https://www.aeso.ca/assets/Uploads/Working-Group-Demand-Curve-Presentation-Final-07282017.pdf> accessed on April 5th, 2019, for a discussion on centralized demand curves considerations in capacity markets.

a linear marginal value is increasing in quantity²⁵. Reasoning locally, a will represent the slope of least-cost solution between the explicit penalty and DR. When drawing a parallel with Chao et al. [1988], a low a would suggest that the retailer is able to discriminate its end consumers according to their willingness to pay either via priority service classes or real-time pricing. This interpretation relates to the discussion on the advantages of *ex post* requirements in terms of end consumers' involvement.

Besides, price elasticity being decreasing in a , the larger a is, the more constrained the buyers are to be close from a certain target²⁶.

For instance, one can define the under procurement as the fact to buy too few quantities with respect to the certainty case. If the slope a is high, the surplus loss is large. Indeed, for a given interval of quantity, the corresponding price interval will spread out when a is increased. In a word, the higher the a is, the higher the cost of under procurement is. About the over procurement (the fact to buy too many quantities with respect to the certainty case), the reasoning is the same. A high a implies that the extra capacities bought may be very expensive with respect to their true marginal value. However, if under and over procurement costs increase with a , they are not equal. For instance, the over procurement cost is bounded by the marginal value of each extra capacity unit (which is at least non-negative), while the under procurement cost can be infinite in theory (e.g. when a is infinite). Then, the adequate choice of the penalty is driven by the public authority's priority that might either be to limit the cost of the mechanism, or to maximize the amount of capacity procured or more probably a mix of the two, meaning that the a should take intermediate values in reality. This is why discussions on capacity market designs insist on the importance of a well-designed penalty [Mastropietro et al., 2016].

As discussed in section 3.2, the issue of optimal SoS emanates from the stochastic nature of the electrical demand. The public authority naturally resorts to forecasting to estimate the optimal level of capacity needed so to meet a given reliability criterion. This is common to all power systems. However, in *ex ante* requirements, this forecast is binding, and its accuracy does not matter for the buyers. On the contrary, it is only indicative in the *ex post* case. In other words, the forecasts cannot be accurate in real life, and the public authority is likely to do her best to send a signal as close to the state of the world as possible. However, it can limit the exposure of the capacity buyers to the forecast errors through the capacity market design. In this sense, the model considers the capacity forecast as a signal with respect to the capacity requirements, not the actual level of capacity needs during the delivery year. The precision of the signal, λ reflects the

²⁵For instance, in France, over procurement might be rewarded through *ex post* trading, meaning that over procurement is valued. In addition, the penalty is piece-wise linear, while a linear marginal value implies that deviations from optimal quantities have a convex cost.

²⁶The demand depending on Z as well, increasing a does not make the buyers necessarily buy more quantities in the model. However, the decision to buy more or fewer quantities will affect more their surplus than before. Thus, a may have a key role in the buyers' preferences in terms of information design.

market design that makes capacity requirements forecasts more or less informative for the capacity buyers. All market participants will form preferences with this respect, knowing all other parameters. In other words, a is known, meaning that the cost of DR is known, and/or the level of the penalty has already been decided. Similarly, the two possible SoW have been announced, and the supply curve is known since it is unaffected by the SoW nor the signal. This last point is the most difficult to verify empirically.

In the model, the uncertainty on future capacity needs is represented via two states of the world affecting the intercept of the marginal value curve. Thus, we assume that the state of the world does change the aggregated demand (and consequently the demand of each buyer) but that it does not affect the willingness to pay for an additional unit²⁷. This formalization is similar to Crampes and Salant [2018] who assume a stochastic demand and a welfare loss function, which is convex in the spread between the realized consumption and the installed capacity²⁸.

Ultimately, the majority-winning rule implies that each unit (or even fraction of unit) can build a separate preference. This assumption does not seem too far from reality in the current market challenges. As highlighted in chapter 1, each technology participates in the capacity market under different rationales, and the increasingly local nature of SoS needs further shifts the focus on unit-based remuneration. Indeed, competition has lead to a decrease in cross-subsidies between the units of a given operator. In other words, profit maximization is increasingly sought at the unit level rather than at the utility or plant level. For instance, the Drax power station in the UK has been abandoning coal-fired generation for profitability –and regulatory– reasons. It has converted from coal firing to biomass firing several (but not all) of its units. It is also proposing to convert up to two of them into gas-fired generating units²⁹. In addition, utilities tend to separate the operation of the different technologies³⁰. While plant operators used to speak on behalf of their generation portfolio, it seems coherent to develop an individual approach where the individual preferences of capacity owners matter and are expressed through public consultations. The objective of the public authority with this respect will be further discussed in section 3.3.7.

3.3.3 Equilibrium

Let q_j be the capacity demanded by the buyer j and $Q = \sum_{i=1}^n q_i$ the total bought capacity. We consider only the symmetric equilibria. Let $Q^*(\mu_h)$ and $q^*(\mu_h)$ be the equilibrium quantities when the buyers have the belief that $\mathbb{P}(Z = z_h) = \mu_h$. Since we

²⁷Equivalently, it implies that the state of the world does not impact how buyers can reduce their electricity peak demand.

²⁸The loss function considered in this chapter would be convex as well since we assume a linear marginal value, with a the constant degree of convexity.

²⁹See <http://repower.drax.com/> accessed on September 25th, 2019.

³⁰For instance, German utilities, E.On and RWE have announced their split-up with renewables and grid operations on the one hand and conventional (thermal) generation on the other. See <https://www.group.rwe/en/the-group/history> accessed on September 25th, 2019.

only consider symmetric equilibria: $Q^*(\mu_h) = \sum_{j=1}^n q^*(\mu_h) = nq^*(\mu_h)$. If there is no ambiguity, we note for the sake of simplicity $Q^* = Q^*(\mu_h)$ and $q^* = q^*(\mu_h)$. The buyers maximize their surplus:

$$\max S(q_j) = \max_{q_j} \int_0^{q_j} D_j^{-1}(x) - F(Q) dx = \max_{q_j} \int_0^{q_j} \mathbb{E}(Z|s) - na x - F(Q) dx$$

Few computations available in chapter D give the following symmetric First Order Condition sFOC:

$$\underbrace{\mathbb{E}(Z|s) - na \times q^*}_{\text{Marginal Value } (V(q^*, n))} = \underbrace{\left(\frac{\partial F(nq^*)}{\partial q} q^* + F(nq^*) \right)}_{\text{Marginal Cost } (C(q^*, n))} \quad (\text{sFOC})$$

With few additional computations (available in chapter D), we obtain the next equilibrium condition with respect to μ_h , with $\zeta = z_h - z_l$:

$$\frac{d q^*}{d \mu_h} = \frac{\zeta}{L'(Q^*)}$$

With $L_i(q^*, n) = \frac{\partial F(nq^*)}{\partial q} q^* + F(nq^*) + na \times q^*$ and $L'(Q^*) = Q^* F''(Q^*) + (n+1) F'(Q^*) + na$ ³¹.

Finally, relations between aggregated quantities and precision are written:

$$\frac{d Q^*}{d \mu_h} = \frac{n \zeta}{L'(Q^*)} \quad (\text{Quantity Derivative})$$

To ensure that the previous expressions are well-defined and that higher beliefs lead to buy a higher amount of quantities (i.e. $\frac{d Q^*}{d \mu_h} > 0$), we make the Assumption 1:

Assumption 1. $L'(Q) > 0$.

Note that Assumption 1 is respected for any convex increasing function F .

Based on the contraction approach used in Gaudet and Salant [1991], the existence of a unique equilibrium in a Cournot oligopsony may be established. Assumption 1 ensures both that the buyers' surplus is strictly concave³² in the quantity (then strictly quasi-concave) and the uniqueness of the symmetric equilibrium:

Theorem 1. *Under Assumption 1, there exists a unique symmetric equilibrium to the Cournot oligopsony with n buyers.*

The interested reader can refer to chapter E for all the proofs. We begin by stating some properties of the equilibrium:

³¹Note that $Q^* F''(Q^*) + (n+1) F'(Q^*) + na = nq^* F''(nq^*) + (n+1) F'(nq^*) + na = \frac{\partial \mathbb{E}(L_i(q^*, n))}{\partial q}$.

³²Concavity is in fact implied by $F'(Q) > -\frac{Q F''(Q) + na}{2n}$ which is not binding. Note that this is always true under Assumption 1.

Lemma 1. *Under Assumption 1, for $s = s_h$ (resp. $s = s_l$), the equilibrium quantities increase (resp. decrease) with the belief μ_h . Furthermore, $\mathbb{E}(Q^*)$ is increasing (resp. decreasing) with respect to λ if $L(Q)$ is concave (resp. $L(Q)$ is convex). Equivalently, $\mathbb{E}(Q^*)$ is increasing (resp. decreasing) if $QF'''(Q) + (n+2)F''(Q) < 0$ (resp. $QF'''(Q) + (n+2)F''(Q) > 0$).*

It is a well-known result in persuasion's literature (see Kamenica and Gentzkow [2011]) that if the public authority's objective function is convex (resp. concave) in the belief μ_h , then the public authority should disclose the maximal (minimal) amount of information. The intuition behind this result is that if the objective function is convex in the belief, the fact that the agents have extreme beliefs will maximize this objective function. Thus, the public authority should disclose information to polarize these beliefs. On the contrary, if the objective function is concave, it is better that the agents have intermediate beliefs, so the public authority limits its information disclosure. In our case, if the public authority is willing to maximize the mean quantity, she should disclose information if and only if her utility is convex in μ_h , i.e. if $\frac{\partial^2 Q^*}{\partial \mu_h^2} > 0$. Then, it corresponds to the case where $\left(\frac{dQ^*}{d\mu_h}\right)' > 0 \Leftrightarrow L''(Q^*) < 0$.

The proof of Lemma 1 can be applied to any other function of μ_h : price, surplus, profit and welfare. It means that for any criterion, we just need to show that this criterion is either convex or concave in μ_h to determine the optimal information disclosure according to this criterion.

A critical feature of Lemma 1 is that the parameter a does not influence the impact of information on quantities. It does affect the quantities at the equilibrium, but because of the linearity of the marginal value, any change in the demand does not change how average quantities evolve with information.

Now, we can study how precision influences the mean price. Using Quantity Derivative:

$$\frac{\partial P^*(\mu_h)}{\partial \mu_h} = \frac{\partial F(Q^*(\mu_h))}{\partial Q^*(\mu_h)} \frac{dQ^*(\mu_h)}{d\mu_h} = F'(Q^*) \times \frac{n\zeta}{L'(Q^*)} \quad (\text{Price Derivative})$$

As for the quantities, the price is increasing in information if the partial derivative of the price with respect to the belief μ_h is increasing. Then, $\frac{\partial \mathbb{E}(P)}{\partial \lambda} > 0$ if $\frac{F'(Q)}{L'(Q)}$ is increasing.

To characterize the influence of information on prices, it is useful to note $\eta(Q, n) = \frac{QF'(Q)}{n} = \frac{F(Q)}{ne(Q)}$. η is the price divided by the product of the number of buyers and the elasticity of the price function ($e(Q) = \frac{\Delta Q}{\Delta F(Q)} \times \frac{F(Q)}{Q} = \frac{F(Q)}{QF'(Q)}$). At the equilibrium, η is simply the markdown (the ability of the oligopsonists to obtain a price below the competitive one). In other words, η represents the degree of market power of the competitors. Its shape (with respect to the supply function) around the equilibrium affects the preferences of both kinds of agents.

Aditionnaly, we note the first and second derivative:

$$\eta'(Q) = QF''(Q) + F'(Q) = L'(Q) - nF'(Q) - an$$

$$\eta''(Q) = QF'''(Q) + 2F''(Q) = L''(Q) - nF''(Q)$$

We state the results with expressions containing L and η . L allows us to derive quite direct results and make links with the paper of Roy et al. [2019]. However, η is helpful to disentangle how the equilibrium and the preferences in terms of information disclosure are affected by market power on the one hand, and the implicit penalty represented by the parameter a on the other hand. To complete the analysis, we provide expressions with respect to the parameter a .

We can now state express the precision effect on the mean price at the equilibrium:

Lemma 2. $\mathbb{E}(P^*)$ is increasing (resp. decreasing) with respect to λ if the price is convex in the belief μ_h , i.e. if $\frac{F''(Q)}{F'(Q)} > \frac{L''(Q)}{L'(Q)}$ (resp. $\frac{F''(Q)}{F'(Q)} < \frac{L''(Q)}{L'(Q)}$).

$\mathbb{E}(P)$ is increasing (resp. decreasing) if:

$$\eta''(Q) < (>) \frac{F''(Q)}{F'(Q)} (\eta'(Q) + an) \equiv \rho$$

The parameter a impacts the result. When a is high, the situation becomes close from perfect competition (so the markdown has less weight in sFOC), and only the convexity of the price function matters in this case (see below Proposition 6).

Corollary 1. $\mathbb{E}(P^*)$ is increasing (resp. decreasing) when:

$$\begin{cases} \text{if } F'' > 0, a > (<) \frac{F'(Q)\eta''(Q)}{nF''(Q)} - \frac{\eta'(Q)}{n} \\ \text{if } F'' < 0, a < (>) \frac{F'(Q)\eta''(Q)}{nF''(Q)} - \frac{\eta'(Q)}{n} \end{cases}$$

When the supply curve F is convex, increasing (decreasing) parameter a increases (decreases) unambiguously the span (of functions F) where the mean price increases with information. Conversely, when the supply curve F is concave, increasing (decreasing) parameter a decreases (increases) unambiguously the span where the mean price increases with information.

In other words, it is more likely that the mean price increases (decreases) with the (explicit or implicit) penalty if F is convex (concave).

For capacity owners, higher expected prices imply higher individual profits and then higher aggregated profit, as we state in Lemma 3:

Lemma 3. If $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$, then individual profits are non decreasing and aggregated profit increases with the precision λ of the signal.

This result drives the discussion about the preferences –the profit-maximizing precision and the majority-winning precision (sections 3.3.5 and 3.3.7). The proof enlightens about the conditions under which a consensus will be established amongst capacity owners.

Now, we have all the tools to derive the preferences of the actors in terms of information design. We start by using the traditional criteria and end with the majority-winning precision.

3.3.4 Buyers' surplus maximization

The theoretical monopsony case helps to emphasize the existence of detrimental effects of competition on the preference for information.

Monopsony

For any total demanded quantity Q , the buyers' surplus is:

$$S(Q) = \int_0^Q D^{-1}(x) - P(Q)dx = \int_0^Q \mathbb{E}(Z|S) - ax - F(Q)dx$$

Few computations give that the derivative with respect to μ_h when there is just one buyer is:

$$\begin{aligned} \frac{\partial S(Q^*(\mu_h))}{\partial \mu_h} &= \frac{d Q^*(\mu_h)}{d \mu_h} \underbrace{(\mu_h \zeta + z_l - a Q^*(\mu_h) - F(Q^*(\mu_h)) - F'(Q^*(\mu_h)) Q^*(\mu_h))}_{=0 \text{ if sFOC}} + Q^*(\mu_h) \zeta \\ \Rightarrow \frac{\partial S(Q^*(\mu_h))}{\partial \mu_h} &= Q_h^*(\mu_h) \zeta \quad (\text{Monopsony's Surplus Derivative}) \end{aligned}$$

Then, $\frac{\partial^2 S(Q^*(\mu_h))}{\partial \mu_h^2} = \frac{n \zeta^2}{L'(Q_h^*(\mu_h))} > 0$ and the following result is straightforward:

Proposition 1. *With a monopsony, i.e. $n = 1$, the buyer's surplus increases with information precision (increases in λ). The monopsony shall always prefer $\lambda = 1$.*

As expected, when the market is unified (i.e. one buyer strategically chooses how to bid with respect to its own marginal value), the buyer's side sees its surplus increase with precision. In this case, information can not hurt: in the absence of competition, additional information always makes profit surplus more effective. This result shows that however the markdown evolves, the monopsony will always be able to use its market power more efficiently with additional information. Nevertheless, this result vanishes for several buyers: in this case, more information can dramatically alter the cost of buying capacity units.

Oligopsony

The presence of other buyers reduces the benefits of increased signal precision on the surplus. It also generates an ambiguity on the sign of the derivative of the surplus with

respect to the precision. The Monopsony's Surplus Derivative simplifies thanks to sFOC for one buyer (for each signal). However, with several buyers ($n > 1$): $\mu_h \zeta + z_l - aQ^*(\mu_h) - F(Q^*(\mu_h)) - F'(Q^*(\mu_h))Q^*(\mu_h) < 0$. By dividing the total surplus by n , and by writing the surplus as a function of individual quantities ($q^* = q^*(\mu_h) = \frac{Q^*(\mu_h)}{n}$): the expected surplus for any buyer j at the equilibrium is:

$$S_j(q^*) = q^* \left(\mu_h \zeta + z_l - \frac{1}{2} a n q^* - F(nq^*) \right)$$

By differentiating with respect to μ_h :

$$\begin{aligned} \frac{\partial S_j(q^*)}{\partial \mu_h} &= \frac{d q^*}{d \mu_h} (\mu_h \zeta + z_l - a n q^* - F(nq^*) - n q^* F'(nq^*)) + q^* \zeta \\ &= - \frac{\partial q^*}{\partial \mu_h} ((n-1) q^* F'(nq^*)) + q^* \zeta \\ &= q^* \zeta \left(1 - (n-1) \frac{F'(nq^*)}{L'(nq^*)} \right) \end{aligned}$$

Proposition 2. *If $n > 1$, $\mathbb{E}(S(Q^*))$ is increasing (resp. decreasing) with respect to λ if the surplus is convex in the belief μ_h , i.e. if $(1 - \frac{(n-1)F'(Q)}{L'(Q)})Q$ is increasing (resp. decreasing). Then, in the first case, the surplus maximizer precision is $\lambda_S = 1$, and in the second case $\lambda_S = \frac{1}{2}$. As well, the surplus is increasing (resp. decreasing) with information precision if:*

$$\eta''(Q) > (<) \rho - \frac{L'(Q)(L'(Q) - (n-1)F'(Q))}{(n-1)QF'(Q)} \equiv \underline{\rho}$$

Corollary 2. *When (i) $(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q) \leq 0$ the surplus is always increasing with information precision.*

Now, note:

$$a_{1s} = - \frac{\sqrt{(n-1)}\sqrt{(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - \frac{F'(Q) - QF''(Q)}{2}$$

and

$$a_{2s} = \frac{\sqrt{(n-1)}\sqrt{(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - \frac{F'(Q) - QF''(Q)}{2}$$

When (ii) $(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q) > 0$, the surplus is increasing (resp. decreasing) with information precision if:

$$\begin{cases} \text{in case where } a_{2s} < 0 \\ \text{in case where } a_{2s} > 0 \text{ and } a_{1s} < 0, \text{ if } a > (<) a_{2s} \\ \text{in case where } a_{1s} > 0, \text{ if } a < a_{1s} \text{ or } a > a_{2s}, (\text{ if } a_{1s} < a < a_{2s}) \end{cases}$$

Increasing parameter a increases unambiguously the span (of η'') where the surplus is increasing with information when $n = 2$ and $F''(Q) > 0$, or when $n > 3$ and $F''(Q) < 0$. When $n = 3$, increasing a increases the preference for information.

In Proposition 2, η is linked to the price function and the penalty represented by the parameter a . If η' increases faster than the price derivative, and that a is high, information is preferred to enjoy η and to avoid the (implicit or explicit) penalty. On the contrary, if buying capacities at the high state is expensive, and that the penalty is low, being aligned with the state of the world matters less. Naturally, increasing the penalty (i.e. fixing a higher a in the model) can reverse the result.

According to Corollary 2, whatever the impact of precision on mean prices, an increase in the implicit penalty a does not always lead to an increased preference for precision. Naturally, Corollary 2 shows that an infinite penalty would make the buyers willing to have the maximal precision, whatever the supply curve is ($a > a_{2s}$ is a sufficient condition). This corresponds to the inelastic marginal value case, where capacity buyers have to procure the required amount. On the contrary, when $a_{1s} > 0$ if a is between a_{1s} and a_{2s} , an increase of a may lead to a preference for no information. To form an intuition on this case, take the case of perfect competition with $\mu_0 = \frac{1}{2}$. If the slope is horizontal ($a = 0$), the buyers prefer full information. Indeed, without information, the gain in the high state (price is lowered) is equal to the loss in the low state. However, there is a cost of under procurement (because valuable capacities in the high states are not bought) that is never compensated. If the slope is increased, now, the price is not equal to $\mathbb{E}(Z)$ anymore. Especially, if the supply curve is increasingly convex, the expected price may grow with information in a dramatic way, leading to less preference for information.

Note that $\underline{\rho}$ will always be lower than ρ when $L'(Q) > 0$, $\forall n \geq 2$ ³³. Thus, a situation where buyers prefer full information while the expected price increases with information can emerge (when $\underline{\rho} < \eta'' < \rho$). By being better aligned with the states of the world, buyers gain enough surplus compared to the increase of the mean price.

3.3.5 Profit maximization

After studying the buyers' side, we look at the usual preferences criterion for owners: the profit maximization. Let λ_P be the signal precision that maximizes the owners' surplus $\mathbb{E}(\Pi(Q)|\lambda)$. When the price increases, every (price-taker) owner prefers the maximal precision as stated by Lemma 3. It then maximizes the profit for all of them individually and it is natural to expect that $\lambda_P = 1$ at the aggregate level as well. In addition, the profit may also increase if the mean price decreases but the quantities purchased increase. Then, we need to characterize the profit maximization precision. The profit is expressed

³³However, for the resolution of the model, Assumption 1 does not need to be verified for all $n \geq 2$, but only for the given level of competition, i.e. the number of buyers n . If $L'(Q, n = 2) < 0$, the second term in $\underline{\rho}$ may be negative for $n > 3$. If F is convex, it can not be negative, so $\underline{\rho} < \rho$. On the contrary, if F is concave, there are cases where $\underline{\rho} > \rho$. Then, buyers may prefer no information while prices are maximal with no information. It might correspond to a situation where η decreases and where buying in the high state is too costly with respect to the marginal value.

as follow (with Q the aggregate quantities sold to the buyers):

$$\Pi(Q) = \int_0^Q F(Q) - F(x)dx$$

The derivative of the expected profit can be written³⁴:

$$\frac{\partial \mathbb{E}(\Pi(Q^*(\mu_h)))}{\partial \mu_h} = \frac{n\zeta Q^*(\mu_h)F'(Q^*(\mu_h))}{L'(Q^*(\mu_h))}$$

We now characterize the necessary condition to an increasing profit with respect to the precision:

Lemma 4. $\mathbb{E}(\Pi(Q)|\lambda)$ is increasing (resp. decreasing) in λ if the profit is convex in the belief μ_h , i.e. if $\frac{QF'(Q)}{L'(Q)}$ is an increasing (resp. decreasing) function. Then in the first case, the profit maximizing precision is $\lambda_P = 1$, and in the second case $\lambda_P = \frac{1}{2}$. As well, the profit is increasing (resp. decreasing) with information precision if:

$$\eta''(Q) < (>) \rho(Q) + \underbrace{\frac{L'(Q)}{Q}}_{>0} \equiv \bar{\rho}$$

Note also that the sufficient condition in Lemma 1 to observe an increase in quantities with respect to precision is sufficient as well to observe an increase in profit. Indeed, few computations show that the previous equation is equivalent to:

$$\eta''(Q) < (>) - nF''(Q) + \underbrace{\frac{\eta'(Q)L'(Q)}{QF'(Q)}}_{>0}$$

We also confirm the result of Lemma 3: higher expected price unambiguously increases the aggregated profit. However, it is not a necessary condition.

Similarly as the buyers's point of view, owners do not systematically increase their preference for information with the slope of the marginal value. However increasing the penalty (i.e. increasing a) favors preference for information for the owners for all increasing power function:

Corollary 3. Note $a_P = \frac{QF'(Q)L''(Q)}{n\eta'(Q)} - \frac{\eta'(Q)}{n} - F'(Q)$. The profit is increasing (resp. decreasing) with information precision if:

$$\begin{cases} \text{In case where } \eta'(Q) > 0, \text{ if } a > (<) & a_P \\ \text{In case where } \eta'(Q) < 0, \text{ if } a < (>) & a_P \end{cases}$$

³⁴Cf. proof of Lemma 4.

When the supply curve F is convex, increasing parameter a increases unambiguously the span (of η'') where the owners prefer information. Otherwise, increasing parameter a decreases the span (of η'') where the owners prefer information if $\eta'(Q) = QF''(Q) + F'(Q) < 0$ ³⁵.

It seems straightforward since any increase in the penalty decreases the relative weight of the markdown in the decision of the buyers. However, we show with Corollary 1 that the mean price may decrease when the penalty increases for a concave price function. Moreover, as we see below in section 3.3.9, perfect competition does not imply that owners prefer precision. Thus, it should be noticed that even if the mean price may decrease, the better alignment of the demand with the state of the world (implied by information and by the higher penalty) will increase the aggregated profit for high a in most of the cases.

Now, after studying the preferences from separated buyers and owners sides, we turn on the characterization of the preferred precision from a welfare point of view.

3.3.6 Economic welfare

The economic welfare is the sum of the buyers' surplus and the owners' profit:

$$\mathbb{E}(W) = \int_0^Q D^{-1}(x) - F(x)dx = \int_0^Q \mathbb{E}(Z|S) - ax - F(x)dx$$

The derivative with respect to μ_h can be found:

$$\frac{\partial \mathbb{E}(W(Q^*(\mu_h)))}{\partial \mu_h} = n\zeta Q^*(\mu_h) \left(1 + \frac{F'(Q^*(\mu_h))}{L'(Q^*(\mu_h))} \right)$$

Consequently, the economic welfare is increasing in the precision if $x \mapsto x \left(1 + \frac{F'(x)}{L'(x)} \right)$ is an increasing function.

Proposition 3. *Whenever $n \geq 1$, if $Q \left(1 + \frac{F'(Q)}{L'(Q)} \right)$ is increasing (resp. decreasing), then the welfare is increasing (resp. decreasing) with information precision. As well, the welfare is increasing (resp. decreasing) with information precision if:*

$$\eta''(Q) < (>) \rho(Q) + \underbrace{\frac{L'(Q)(L'(Q) + F'(Q))}{QF'(Q)}}_{>0} \equiv \bar{\rho}$$

Lemma 2 and Proposition 3 imply that if the mean price increases with the precision, the welfare increases as well. By Lemma 3, when the mean price increases with information, the profit increases as well. Due to the non-strategic role of the supply-side, the welfare becomes naturally higher as well. Even if the mean price decreases, a better alignment of the demand with the state of the world may also increase the welfare.

³⁵This condition is not verified for any increasing power functions. Note that $QF''(Q) + F'(Q) = 0$ for the function $F(Q) = \log(Q)$.

Besides, information also can reduce the welfare. In this case, profit is also reduced with information ($\frac{\partial W}{\partial \lambda} < 0 \Rightarrow \frac{\partial \Pi}{\partial \lambda} < 0$). What buyers earn (thanks to the average increase of markdown) does not compensate for the losses of the owners' side.

Concerning the parameter a , similar qualitative results as in Corollary 3 appear. Indeed, an increase of a may result in preference for information from a welfare point of view:

Corollary 4. *When (i) $\eta'(Q)^2 + 4QF'(Q)L''(Q) \leq 0$, the welfare is always increasing with information precision*

Now, note

$$a_{1w} = -\frac{\sqrt{\eta'(Q)^2 + 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - F'(Q)$$

and

$$a_{2w} = \frac{\sqrt{\eta'(Q)^2 + 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - F'(Q)$$

When (ii) $\eta'(Q)^2 + 4QF'(Q)L''(Q) > 0$ the welfare is increasing (resp. decreasing) if:

$$\begin{cases} \text{in case where } a_{2w} < 0 \\ \text{in case where } a_{2w} > 0 \text{ and } a_{1w} < 0, \text{ if } a > (<)a_{2w} \\ \text{in case where } a_{1w} > 0, \text{ if } a > a_{2w} \text{ or } a < a_{1w}, (\text{ if } a_{1w} < a < a_{2w}) \end{cases}$$

When the supply curve F is convex, increasing parameter a increases unambiguously the span (of η'') where the welfare increases with information. Otherwise, increasing parameter a decreases the span (of η'') where the welfare increases with information if $\eta'(Q) = QF''(Q) + F'(Q) < 0$.

We see that if a is set high enough, the welfare criterion will favor information precision. Generally, a preference for a low level of information from a welfare perspective is a way to limit the (buyers') market power. Indeed, if the supply curve is (convex and) increasing enough, we can see that precision does not affect much the level of quantity bought, but that the price can be moved dramatically. In this case, limiting market power is done via limiting information precision. Naturally, it implies that taking the risk of not being aligned with the state of the world and increasing the probability of rationing if the state of the world is high. However, according to Corollary 4, resorting to a lower degree of information might not be necessary if the penalty is set high enough.³⁶

Finally, we can order the different thresholds which shape the preferences considering the different surpluses:

$$\underline{\rho} < \rho < \bar{\rho} < \bar{\bar{\rho}}$$

³⁶If the parameter a remains low despite a high explicit penalty, resorting to DR might be cheaper than paying the penalty. In this situation, the CM might be able to unleash significant amounts of untapped DR. This explanation directly relates to the discussion about the advantages to make bear (to create) the risk on buyers by setting *ex post* requirements.

Note that there is an agreement between buyers and owners for maximal precision in the interval $(\underline{\rho}, \bar{\rho})$.

Nevertheless, we consider heterogeneous capacity owners in this model (as it is the case in real-life). Therefore, preferences exhibited by the aggregate profit criterion may not reflect the preferences of *all* the individual owners³⁷. In the next section, we determine under which conditions such a disagreement emerges and propose an alternative to the profit maximization criterion.

3.3.7 Public authority's objective functions

In the economic literature, the public authority is often described as seeking welfare maximization. This approach is nuanced by institutional economists who argue that a wide range of factors such as history and culture affects the objective function of the public authority, which can then differ from welfare maximization. In the context of capacity markets, Newbery [2016] warns against a tendency of the central authority to over procure capacity, as a way to avoid the political consequences of a black-out. This is one example among many that welfare maximization might not be its only objective. For instance, chapter 1 has discussed how different the approaches to the SoS problem can be. In this sense, when a public authority is willing to create a capacity market, it has to define the aims of this capacity market, accounting for the characteristics of the country, its historical background, as well as its own view about the future.

These various aims can be summarized in an objective function of the public authority. Here, we present simplified examples of objective functions:

- Quota rule: it is the decision process based on the approval of a given proportion (50%, 66%, 90%... for example) of voters. For instance, Nitzan and Paroush [1984] determine the optimal number of voters needed to approve a proposition for each situation. In their framework, the voters are homogeneous and have a given probability to vote for the incorrect decision and there is a bias in favor of statu quo. In our case, the capacity owners are heterogeneous and know their favorite precision. The statu quo may be to give perfect information. Then, the public authority may choose the minimal necessary proportion of capacity owners choosing the same $\lambda_C \neq 1$ to modify the design. For instance, a stringent quota rule could require a share close to unanimity to choose *ex post* requirements as a design. This would give greater weight to peak generators which might be more concerned about their own survival than aggregate profit maximization if the capacity price hardly covers their profitability gap. We know that the mean price can be decreasing in information precision. Naturally, in this case, profit-maximizing owners would prefer *ex post* requirements. Nevertheless, *ex ante* requirements enable more owners to sell and

³⁷The assumption of homogeneity of the buyers' side makes that no disagreement can emerge among buyers. However, it seems that differences in the buyers' side matter less than differences between capacity owners, due to the structural heterogeneity of the generators that rely on different technologies.

generates more certainty (since the level of required quantities is known *ex ante*). These two elements may result in a higher level of SoS. Paradoxically, the peak generators' profits may still be larger with *ex ante* requirements (see below the frame *majority-winning criterion*). These considerations may lead the public authority to overweight the peak generators' (dis-)agreement with *ex ante* requirements in the decision process.

- **Technologies:** the objective of the public authority might be biased towards given technologies. This is a recurrent criticism made to CMs. In this case, the public authority might only account for the preferences of the subset of actors operating such technology(ies). For instance, some authors argue that capacity markets should favor flexible technologies [Buck et al., 2015]. Indeed, those are direly needed to meet the SoS objective on a shorter timescale. Similarly, the capacity market could be designed with the side objective to meet the emission targets. The public authority could then favor green technologies.
- **Maximize Quantities:** this objective is coherent with a public authority that would fear the political consequences of a black-out more than the welfare consequences of such a choice. Alternatively, it is also a way to favor capacity owners.
- **Minimize Prices:** this objective function would be in line with greater importance of the retailers' surplus in the public authority's considerations. Limiting the cost of the measure is also a way to protect end consumers.

Among those examples, some objective functions clearly require further knowledge about individual actors' preferences. The most common tool to uncover those is public consultations. The preferences expressed during the consultation can then be aggregated in different ways to match the public authority's objective.

As an illustration, we study a particular case of the quota rule: the majority rule (i.e. the proportion of voters needed to change the design should be at least 50%). However, we discuss as well the implications of a more binding quota rule (i.e. with a quota higher than 50%). We make the analysis for the special case where $\mu_0 = \frac{1}{2}$. We consider in the rest of the chapter that each capacity owner has the same weight in the selection process.

Majority-winning criterion

In a discrete world, the majority-winning precision λ_C can be defined as the precision of public information that maximizes the number of capacity owners satisfied with respect to their bid. By contrast to the previous condition of maximizing the owners' surplus, this equates satisfying the greater number of them. The majority-winning procedure gives new insights about the preference of capacity owners with respect to the market design.

In the simplified framework, where each owner bids one unit, each owner has the same weight in the preference of the majority. As stated below, when the mean price increases with information (so the profit increases for each owner by Lemma 3), they all agree, and the majority-winning precision will be 1.

Though, if the mean price decreases with information precision (i.e. $\frac{F'(Q)}{L'(Q)}$ decreases or $\eta''(Q) > \rho(Q)$), owners may disagree about the optimal precision. In this case, the majority-winning precision depends on the distribution of the bids.

When $\mu_0 = \frac{1}{2}$ consider $\lambda = 1$ and $\lambda = \frac{1}{2}$ when $\eta''(Q) > \rho(Q)$. First, recall that:

$$F(Q^*(0)) < F(Q^*(\mu_0)) < F(Q^*(1))$$

Let $\hat{b} \in [F(Q^*(0)); F(Q^*(\mu_0))]$ be the bid for which a owner is indifferent between the two information structures:

$$\underbrace{F(Q^*(\mu_0)) - \hat{b}}_{\text{Individual profit when } \lambda=\frac{1}{2}} = \underbrace{\mu_0(F(Q^*(1)) - \hat{b})}_{\text{Individual profit when } \lambda=1} \Rightarrow \hat{b} = \frac{F(Q^*(\mu_0)) - \mu_0 F(Q^*(1))}{1 - \mu_0}$$

On the one hand, owners (i) with a bid below than \hat{b} will prefer the lowest precision since their expected profit is higher when $\lambda = \frac{1}{2}$. Indeed, as mentioned in the proof of Lemma 3, the ones with a bid below $F(Q^*(0))$ always sell in both states of the world. Thus, they want to maximize the mean price. The ones whose the bid is higher than $F(Q^*(0))$ will sell, by definition, only if the price is higher than $F(Q^*(0))$. Their bid is such that:

$$F(Q^*(\mu_0)) - \hat{b} > \mu_0(F(Q^*(1)) - \hat{b})$$

On the other hand, owners (ii) bidding higher than \hat{b} (but below $F(Q^*(1))$) are such that their bids respect:

$$F(Q^*(\mu_0)) - \hat{b} < \mu_0(F(Q^*(1)) - \hat{b})$$

Thus, even if they do not sell their capacities in both states of the world, these owners prefer the highest precision.

Note that if $\mu_0 \geq \frac{1}{2}$, the owners prefer either $\lambda = \frac{1}{2}$, either $\lambda = 1$. The reason is that $\lambda = 1$ maximizes: $\mathbb{P}(s = S_h) \times (F(\mu_h(s_h)) - b)$, since $\mathbb{P}(s = S_h)$ increases with λ in this case ($\frac{\partial \mathbb{P}(s=S_h)}{\partial \lambda} = 2\mu_0 - 1 > 0$).

In our context, Q is the number of owners that are able to sell their capacity (bid under the clearing price). Thus, if we define $m(Q)$ as the difference between the size of these two groups of owners (i) and (ii), we get the λ_C that corresponds to the

majority rule, with respect to the positivity of L . Let:

$$m(Q) = \underbrace{\int_{\hat{b}}^{F(Q^*(1))} F^{-1'}(b_i) db_i}_{\text{Preference for } \lambda=1} - \underbrace{\int_0^{\hat{b}} F^{-1'}(b_i) db_i}_{\text{Preference for } \lambda = \frac{1}{2}} = Q^*(1) - 2F^{-1}(\hat{b})$$

Here, if $m(Q) > 0$ (resp. $m(Q) < 0$), the preferred precision is 1 (resp. $\frac{1}{2}$).

This result can be extrapolated to any value of $\mu_0 \geq \frac{1}{2}$. However, if $\mu_0 < \frac{1}{2}$, the probability of getting a high signal decreases when the precision increases. It means that a part of the owners who prefer 1 to $\frac{1}{2}$ will prefer another λ . As well for a part of the owners who prefer $\frac{1}{2}$ to 1 (see chapter E).

We can now state the next result:

Lemma 5. *When $\mu_0 = \frac{1}{2}$, whenever $n \geq 1$, if (1) $\frac{F'(Q)}{L'(Q)}$ increases, $\lambda_C = 1$. If (2) $\frac{F'(Q)}{L'(Q)}$ decreases, $\lambda_C = 1$ when (2i) $m(Q) > 0$ and $\lambda_C = \frac{1}{2}$ when (2ii) $m(Q) < 0$.*

Owners' preferences can be summed up in the next proposition derived directly from Lemma 4 and from Lemma 5 since $\left(\frac{F'(Q)}{L'(Q)}\right)' < \left(\frac{QF'(Q)}{L'(Q)}\right)'$:

Proposition 4. *When $\mu_0 = \frac{1}{2}$, whenever $n \geq 1$, if (1) $\frac{F'(Q)}{L'(Q)}$ increases ($\eta''(Q) < \rho(Q)$), $\lambda_C = \lambda_P = 1$. If (2) $\frac{F'(Q)}{L'(Q)}$ decreases but $\frac{QF'(Q)}{L'(Q)}$ increases ($\rho(Q) < \eta''(Q) < \bar{\rho}(Q)$), $\lambda_C = \lambda_P = 1$ if $L(Q) > 0$ and $\lambda_P = 1 > \lambda_C = \frac{1}{2}$ if $L(Q) < 0$. If (3) $\frac{QF'(Q)}{L'(Q)}$ decreases ($\bar{\rho}(Q) < \eta''(Q)$), $\lambda_C = 1 > \lambda_P = \frac{1}{2}$ if $m(Q) > 0$ and $\lambda_P = \lambda_C = \frac{1}{2}$ if $m(Q) < 0$.*

In other words, if the price increases with information precision, all the owners will prefer full information: both the profit-maximizing and the majority-winning criteria require the maximal precision. When the price decreases with information precision ($\frac{F'(Q)}{L'(Q)}$ decreases), but the profit is nonetheless increasing in λ then again, the majority and profit maximization criteria agree towards full information if $m(Q) > 0$. They would however disagree if $m(Q) < 0$ ($\lambda_P = 1 > \lambda_C = \frac{1}{2}$). When the profit decreases with information precision, i.e. η'' is relatively high enough, the lowest precision will always maximize the profit ($\lambda_P = \frac{1}{2}$) while the majority-winning criterion will depend on the relative size of the owner groups preferring each level of information: $\lambda_C = 1$ if $m(Q) > 0$ or $\lambda_C = \frac{1}{2}$ if $m(Q) < 0$.

3.3.8 Model results

As highlighted by the previous sections, preferences in terms of information precision depend very much on the curvature of the supply curve. Summarizing Lemmas 1 and 2, there are six distinct cases concerning the impact of information on equilibrium prices

and quantities.

Proposition 5. *We note six different cases such that:*

| <i>If (a) $F'' > 0$</i> | <i>If (b) $F'' < 0$</i> |
|--|--|
| (a1) $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$ and $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$. | (b1i) $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$ and $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$. |
| (a2i) $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$ and $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$. | (b1ii) $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$ and $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0$. |
| (a2ii) $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$ and $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0$. | (b2) $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$ and $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0$. |

| η'' | $-nF''$ | | | ρ |
|-----------------------------------|------------------|------------------|------------------|------------------|
| <i>if $F'' > 0$</i> | $\partial Q > 0$ | $\partial Q < 0$ | $\partial Q < 0$ | $\partial Q < 0$ |
| | $\partial P > 0$ | $\partial P > 0$ | $\partial P < 0$ | $\partial P < 0$ |
| | (a1) | (a2i) | (a2ii) | |
| η'' | ρ | | | $-nF''$ |
| <i>if $F'' < 0$</i> | $\partial Q > 0$ | $\partial Q > 0$ | $\partial Q < 0$ | $\partial Q < 0$ |
| | $\partial P > 0$ | $\partial P < 0$ | $\partial P < 0$ | $\partial P < 0$ |
| | (b1i) | (b1ii) | (b2) | |

Output Derivatives w.r.t. λ

We make the following statements:

If (a) $F'' > 0$, then $\frac{\partial \mathbb{E}(Q^)}{\partial \lambda} > 0 \Rightarrow \frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$ and $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0 \Rightarrow \frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$.*

If (b) $F'' < 0$, then $\frac{\partial \mathbb{E}(P^)}{\partial \lambda} > 0 \Rightarrow \frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$ and $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0 \Rightarrow \frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0$.*

Unambiguous satisfaction of owners with precision (a1, b1i)

When the mean price and the mean quantities are both increasing with precision (a1, b1i), the profit-maximizing and the majority-winning preferences will be aligned. Intuitively, a higher price boosts the profit of owners already selling and higher quantities enables new owners to enter the market. When F is convex, the case (a1) will correspond to intervals where the curve becomes increasingly linear ($F'' \rightarrow 0^+$). The situation (b1i) is, however, unlikely for a concave supply curve because it would require F'' to strongly decrease. Indeed, under the model assumption, F is increasing so F'' cannot strongly decrease on a large interval. For instance, the square root or logarithm function would never lead to (b1i).

Unambiguous satisfaction of buyers with precision (a2ii, b2)

Buyers gain surplus when both quantities and prices decrease with precision (according to Proposition 2 since $\underline{\rho} < \rho$). This may be at the expense of the aggregated profits (and the welfare) since capacity owners would then sell fewer quantities at a lower mean price. When F is convex, this corresponds to a strong increase in F''

while if it is concave, such a situation would appear when F becomes flat ($F'' \rightarrow 0^-$).

Ambiguous preferences (a2i, b1ii)

In (a2i, b1ii), equilibrium outputs (price and quantities) move in opposite directions when precision increases: the preferences will then depend on the relative weight of the two effects. For example, when buyers are better informed, the concavity of the supply curve may result in a large decrease of the price when the state of the world is low and in a large increase of the quantities sold when the state of the world is high: the aggregated profit may increase when mean quantities increase enough. These cases correspond to situations where F'' does not move sharply.

After giving some intuition about the preferences by distinguishing convex and concave cases, we characterize the preferences. Investigating four different criteria of optimal information disclosure, we highlight the existence of four distinct thresholds for the second derivative of η :

$$\rho = \frac{F''}{F'}(\eta' + an) \quad \bar{\rho} = \rho + \frac{L'}{Q} \quad \underline{\rho} = \bar{\rho} - \frac{L'(L' - (n-1)F')}{(n-1)QF'} \quad \bar{\bar{\rho}} = \bar{\rho} + \frac{L'(L' + F')}{QF'}$$

As noted above, few computations show that $\underline{\rho} < \rho$ under Assumption 1 for all n .

| $\eta''(Q)$ | | $\underline{\rho}$ | ρ | $\bar{\rho}$ | $\bar{\bar{\rho}}$ |
|------------------|---------------|---------------------------|-----------------|---------------------------|---------------------------|
| Welfare | | $\lambda_W = 1$ | $\lambda_W = 1$ | $\lambda_W = 1$ | $\lambda_W = \frac{1}{2}$ |
| Buyers' Surplus | | $\lambda_S = \frac{1}{2}$ | $\lambda_S = 1$ | $\lambda_S = 1$ | $\lambda_S = 1$ |
| Owners' Profit | | $\lambda_P = 1$ | $\lambda_P = 1$ | $\lambda_P = 1$ | $\lambda_P = \frac{1}{2}$ |
| Majority-Winning | if $m(Q) > 0$ | $\lambda_C = 1$ | $\lambda_C = 1$ | $\lambda_C = 1$ | $\lambda_C = 1$ |
| | if $m(Q) < 0$ | | | $\lambda_C = \frac{1}{2}$ | $\lambda_C = \frac{1}{2}$ |

Table 3.3: Maximizing precision for $n > 1$

Table 3.3 sums up the previous results and gives an insight about the disagreement between buyers and owners and, amongst heterogeneous owners. It only represents the buyers' surplus for $n > 1$ since the monopsony always prefers full information. Full information is preferred by both the buyers' side and the owners' side (in terms of surplus) when the relative increase of η derivative is approximately the same as the relative increase of the price derivative (i.e. $\frac{\eta''(Q)}{\eta'(Q)} \simeq \frac{F''(Q)}{F'(Q)}$). When Q is large enough, it becomes $\frac{F'''(Q)}{F''(Q)} \simeq \frac{F''(Q)}{F'(Q)}$ ³⁸. Then the supply curve should be such that derivatives have relatively the same behavior until the order 3. However, conflicts arise between buyers and owners when this is not true anymore. For a rather slowly increasing (or decreasing) η ($\eta''(Q)$ small) with respect to the supply function, no information will maximize the buyers' surplus while the welfare, as well as all owners' preference criteria, will be higher under full information. Recalling that the mean quantities increase with λ when $\eta'' < -nF''$, we deduce in this case that Q_h increases faster than Q_l decreases. Recalling also that the marginal gain to increase the quantity is everywhere the same, the gain from getting more

³⁸It implies that the price function is K-bilipschitz with K around 1 up to the order 3.

quantities in the high state (and getting less in the low state) is offset by paying more in the high state (with a price decrease in the low state not large enough). Because of the presence of competitors, when η does not increase rapidly enough, the buyers are worse off with information³⁹. Unsurprisingly, we find the owners' profit on the other side of the spectrum. Indeed, in this example, an increase in the mean quantities makes the profit higher. $\eta'' < \rho$ correspond to cases (a1), (a2i) and (b1i). As noted above, (b1i) is unrealistic. It means that in the concave case, we do not expect disagreement from the buyers' side (cases (b1ii) and (b2) are such that buyers prefer information). In addition, we do not expect that all the criteria will be in favor of information. From what we have described above, we deduce that, in the convex case, disagreement from the buyers is likely when the supply curve becomes linear rapidly (roughly case (a1)).

On the contrary, when η is increasing quickly (with respect to the supply function), no information is chosen by owners as a whole. Thus, the more F'' increases, the more the owners might be disadvantaged by precision. It corresponds to situations where the supply curve increases rapidly (and is convex) (roughly case (a2ii)) or where the supply curve becomes rapidly flat (and is concave) (roughly case (b2)).

For the welfare-maximizing criterion to choose no information, an even steeper change is needed. The welfare is more influenced by the owners than the buyers because of the strategic behavior of the latter. However, at the moment of designing the capacity remuneration scheme, the supply curve is not known yet and the system operator has to decide for the precision of information. The welfare cannot be deduced either, and the solution found is often to ask the stakeholders about their preferences directly. This is where the majority-winning criterion takes all its purpose.

When considering the majority-winning criterion, conflicts can arise more often than in the surplus cases. In practice, in CRMs, the uncertainty on the intercept is unlikely to be big enough for the group of owners preferring full information to overweight the group of owners, which are certain to sell under both states of the world. In other words, if the public authority puts all the owners in a room and makes them vote for their preferred level of information, it is more likely to be "no information" than under the usual profit-maximizing criterion. It follows that, alone, a public consultation might not be fully trustworthy and need to be completed by a good knowledge of both the economics at stake and the system specificities in order to knowingly weight each actor's view and advice.

Interestingly, buyers and owners can agree when profits are considered, but they may disagree when majority-winning is the decision-making process and vice versa.

³⁹To understand why, imagine the same equilibrium with a high signal (i.e. the same couple (price, quantity)) with two different supply curves and assume an increase in the precision: sFOC indicates that quantities will increase more in the case of the softest curve since the price derivative is lower. Under competition, this increase may be high enough (because all the buyers increase their demand together) to offset the fact that the supply curve increases at a lower rate and may lead to a higher price with the softest curve.

3.3.9 Large number of buyers

When we move away from an oligopsony with few buyers (as n increases), results simplify. First, let us study the effect of n on the equilibria quantities:

Lemma 6. *Total quantities at the high and low equilibria are increasing concave functions with respect to n .*

The fact that quantities increase with the number of buyers is in line with the existing literature on oligopsonies (see Okuguchi [2000]). The proof uses sFOC with $Q = nq$.

Individual markdown decreases with respect to n . When n increases, the share of each individual buyer decreases and an increase of the market price (by increasing marginally an individual consumption) affects less the buyers than if they buy individually large amounts of quantities. One can notice that the derivative goes to zero when n becomes large enough, meaning that in a competitive state, additional buyers stop increasing the aggregated demand. Indeed, concavity emerges naturally since even if a new buyer has the same incentives to meet the needed demand as any previous entering agent, price increasing (and then the net incentives decrease), the new equilibria shift upward more slowly when n increases.

This may seem coherent with the fact that buyers are more incentivized to get capacities when they are numerous. Indeed, the decreasing marginal value curve represents the decreasing willingness to pay for additional units of capacity. The fact that all buyers highly value the first capacity units means that buyers are individually ready to get more capacities (relative to their market share) for a large n . In this case, more aggregated capacities are sold.

When n is large enough, the effect of information on equilibria outputs simplifies:

Lemma 7. *For any thrice differentiable supply curve, it exists $N \in \mathbb{N}$ such that $\forall n > N$: If (a) $F'' > 0$, then (a2i): $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$ and $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$. If (b) $F'' < 0$, then (b1ii): $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0$ and $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$.*

When n is large enough, with respect to the curvature of the bid function, outputs can move only in one direction. Results become more intuitive: mean prices and mean quantities move in opposite ways with information precision. If the supply curve is concave, more information increases the quantities dramatically in the high state (with limited prices increase) and slightly lowers the quantities when the state of the world is low (with prices dropping a lot). The reverse mechanism appears when the supply curve is convex.

Following Lemma 7 and the results of the previous subsections, we can derive the preferences of the agents when n is large enough as well as the optimal precision when considering welfare:

Proposition 6. *When n is large enough, preferences can be characterized with respect to the convexity of the bid function:*

| F'' | | $-\frac{F'(F'+a)}{aQ}$ | 0 | $\frac{F'+a}{Q}$ | |
|------------------|---------------|---------------------------|---------------------------|------------------|---------------------------|
| Buyers' Surplus | | $\lambda_S = 1$ | $\lambda_S = 1$ | $\lambda_S = 1$ | $\lambda_S = \frac{1}{2}$ |
| Owners' Profit | | $\lambda_P = \frac{1}{2}$ | $\lambda_P = 1$ | $\lambda_P = 1$ | $\lambda_P = 1$ |
| Majority-Winning | if $m(Q) > 0$ | $\lambda_C = 1$ | $\lambda_C = 1$ | $\lambda_C = 1$ | $\lambda_C = 1$ |
| | if $m(Q) < 0$ | $\lambda_C = \frac{1}{2}$ | $\lambda_C = \frac{1}{2}$ | $\lambda_C = 1$ | $\lambda_C = 1$ |
| Welfare | | $\lambda_W = 1$ | | | |

Table 3.4: Maximizing precision under perfect competition

When the market power vanishes, information can not hurt the welfare when this competition effect is null. Then, decreasing the precision of information reveals that the policy maker favors one side or that the market is not competitive enough.

As discussed in section 3.1, it is decentralization that introduces the issue of competition in this market. In this sense, the perfect competition case is of special interest when considering capacity markets. For not having strategic behaviors on the buyer-side, there is an obvious relationship between the perfection competition case and the centralized capacity market case where a benevolent central planner directly procures the capacity. If her objective function is the welfare and there is no asymmetry of information, then the two situations are equivalent.

3.4 Case study: model parametrization

In a simple framework, we have shown that the welfare-maximizing design can be difficult to derive from public consultations. Indeed, it might be aligned with the profit-maximizing design but due to capacity owners' heterogeneity, the majority-winning design might not even be profit-maximizing. In addition, *ex post* requirements are never consensual: their implementation is equivalent to favoring one or the other type of actors. The model results are sensitive to the level of parameters, meaning that generalizing the results to actual situations is not straightforward. Apprehending the empirical likelihood of each situation requires to investigate plausible situations. Indeed, the theoretical model has been kept rather general, with limited assumptions on the parameters. Such implicit consideration of market characteristics makes the model handy and adaptable but limits the intuitiveness of the results.

With this respect, German data from 2010 is used to parametrize the model and understand to what extent specific assumptions on parameters might affect preferences on information precision. Using data from 2010 presents a double advantage: (i) it sets aside discussions on the interactions between renewables integration and security of supply, (ii) it also prevents from over-interpreting the results in terms of policy recommendations. Indeed, reasoning in a hypothetical framework -Germany never did implement a capacity

market- allows testing a broader scope of hypotheses than would a real-life capacity market allow. Mainly, the data derived from existing markets would already account for the implemented design, be it with *ex ante* or *ex post* requirements, and, as such, be biased in some way. We thus build up a hypothetical consultation process where preferences are assessed under different levels of demand, penalty (or cost of voluntary peak shaving), and competition. Plants are assumed to have only two sources of income: energy and capacity revenues. Thus, they bid their profit gap on the capacity market as in a competitive environment [Keles et al., 2016; Iychettira et al., 2014; Hach and Spinler, 2016]. Capacity buyers being the strategic side of the model, we test different values for the slope, the intercept, or the degree of competition. As in the majority-winning case, we restrict the prior to an equiprobability of the states of the world ($\mu_0 = \frac{1}{2}$). The objective is to mimic different market conditions, in a way different designs proposed in a public would, to bring out how the actors preferences in terms of requirement definition are affected. The reader uninterested on the assumptions around parametrization can go directly to the results in section 3.4.3.

3.4.1 Supply-side assumptions

The model allows for all types of supply-side behavior as long as the supply curve is continuous and unaffected by the signal. For tractability purposes, this case study will consider a competitive situation on the supply-side⁴⁰.

In this context, capacity owners bid their participation constraint, which can be approximated by the profitability gap in a market that already provides the right availability incentives. This complies with the zero profit competitive paradigm and allows building a supply curve with transparent assumptions. In an exercise similar to Joskow [2007], we build up an estimation of the profit gap. However, two main elements differ from Joskow's methodology. First, capacity owners are assumed to be remunerated only for their energy produced and capacity, disregarding ancillary, and balancing revenues. Second, the use of representative units (base, intermediate, and peaking units) is too restrictive for our purpose. We thus use He et al. [2013]'s "Dual Exponential" estimation of the merit order⁴¹ to generate a continuous merit order. The day-ahead market revenues are computed based on 2010 hourly price data from EPEX Spot and abstracting from non-linearities: ramping costs are disregarded. A unit is considered as producing and earning money each time the price is higher than its marginal cost. To account for fixed operation and maintenance costs (O&M), the producers as represented by the "Dual Exponential" are

⁴⁰Although CRMs commonly mitigate supply-side market power, the absence of strategic behavior from capacity owners remains a strong assumption (which is not required by the theoretical model).

⁴¹Based on publicly available data such as EEX (European Energy Exchange) hourly prices for 2010, available generation capacity, outages, historical production, wind and solar production, vertical load, consumption, and exports, they empirically estimate the German merit order from 2010 considering that prices are function of a normalized load. The vertical load is increased with exports and nuclear and lignite unavailabilities. The maximum value of the resulting "equivalent transmission grid load" is then used to normalize the data set. Comparing three specifications, they find the "Dual Exponential" to perform better. See He et al. [2013] for further details.

assigned a technology based on installed capacity in Germany ordered according to their merit. Figure G.1 summarizes the main computations. For instance, the first 26% of the merit order are assumed to reflect renewable units bidding. This is because geothermal, wind and solar made up to 26% of installed capacity in 2010 according to the German Federal Ministry for Economic Affairs and Energy - BMWi. Then follows hydropower, nuclear, coal, biomass, gas and oil-fired power plants. Once each unit corresponds to a category, fixed O&M are assigned and deduced from the revenues to derive a net rent (see table 3.5). Renewables are assumed to bear no fixed costs because subsidies ensure their profitability. Similarly, hydropower is known to bid at opportunity cost and will effectively recover its full costs: a zero fixed cost is assumed for those two technologies by simplification. The resulting net rent for each unit (fixed costs being allocated on a fuel basis) is represented in figure G.1. When considering the day-ahead market as the only source of revenues, more than 20% of the installed capacity is not profitable⁴².

Considering that the market participants bid their profit gap on the capacity market, their bid is deducted from the net rent: it is the maximum between zero and the opposite of the net rent. Those bids are then ordered from the lowest to the highest, and the corresponding capacity is derated⁴³ with a fuel-specific coefficient (see table G.1). Abstracting from already profitable units as well as possible new entrants (investments), the resulting distribution is approximated on three intervals with a cubic spline function to obtain a thrice differentiable monotonic supply curve⁴⁴. The resulting spline approximation is represented along the estimated bidding curve in figure 3.2.

| Fuel | Derating | Fixed O&M (€/kW) |
|---------|----------|------------------|
| Nuclear | 0.8524 | 82.1 |
| Coal | 0.8758 | 30 |
| Gas | 0.9293 | 20 |
| Oil | 0.8804 | 15 |

Table 3.5: Cost assumptions for Germany in 2010 based on Villavicencio [2017] and the EMR delivery body

3.4.2 Demand-side assumptions

In the model, the behavior of the demand-side is embedded in the linear marginal value results from 5 parameters: the slope (a), the signal (s_h or s_l), the precision of the signal (λ), the uncertainty ($z_h - z_l$) and the level of competition on the market (n). As discussed, model parameters are exogenous as they are affected by the capacity market design.

⁴²It is noticeable that the alternative specifications proposed by He et al. [2013] would lead to similar results.

⁴³Using the UK capacity market deratings as in <https://www.emrdeliverybody.com/Lists/Latest%20News/Attachments/114/Capacity%20Market%20Auction%20Guidelines%20July%207%202017.pdf> last accessed on February 4th, 2019.

⁴⁴The spline coefficients are summed up in table G.1. Using splines could actually provide a finer approximation, but this would be at the expense of monotonicity.

Mainly, the level of the intercept depends on the capacity target. In addition, the higher the non-compliance penalty, the greater the slope (a) of the marginal value. In the absence of a capacity market, or even a reliability target –as in Germany–, none of the parameters are straightforward so several cases will be discussed. Several capacity market designs are compared to assess the sensitivity of preferences regarding requirement definition. They differ in terms of non-compliance penalty level, competition level, quantity target, and degree of uncertainty. Some of those elements are calibrated –to some extent– to the German situation in 2010, others are extrapolated from existing CRMs.

Various sources are used to select possible capacity targets and thus derive the corresponding intercepts. Indeed, the use of past data provides the advantage of knowing the risk realization (peak demand) and eases the estimation of potential targets in the absence of official reliability criterion. For instance, the European Network of Transmission System Operators's (ENTSO-e) transparency platform provides hourly demand for Germany with a 91% coverage: the maximum hourly demand over 2010 (around 79.9 GW) is used as a minimum capacity requirement in this case study. Scaling it up to cover 100% of the German demand leads to a peak demand of roughly 87.1 GW. This lends in the second interval. In turn, the IEA considers that a reasonable reserve margin⁴⁵ is between 15 to 20% (see figure G.2 from International Energy Agency [2010]). The two extremes of what the IEA considers a "reasonable" interval provides the two additional points⁴⁶ to test the sensitivity of the preferences to the level of procurement (i.e., the local shape of the supply curve). The set of capacity targets considered are $Q_1^t = 79.9$, $Q_2^t = 87.1$, $Q_3^t = 100.1$ and $Q_4^t = 104.5$ as displayed in figure 3.2.

With respect to uncertainty, we consider three situations: (i) no uncertainty, meaning that $z_h = z_l = aQ_i^t + F(Q_i^t)$, (ii) 1% uncertainty where $z_h = F(1.01Q_i^t) - 1.01aQ_i^t$ and $z_l = F(0.99Q_i^t) - 0.99aQ_i^t$, (iii) 2% uncertainty with $z_h = F(1.02Q_i^t) - 1.02aQ_i^t$ and $z_l = F(0.98Q_i^t) - 0.98aQ_i^t$. As a benchmark for such levels, RTE [2015] presents the official forecasts of total obligation for delivery years 2016 to 2020. The high and low scenarios deviate from the baseline by less than 3% (see figure G.3). This is considered as an upper bound bearing. For the sake of simplicity, the corresponding situations will always be called through the corresponding target (Q_i^t).

With respect to the slope (a), centralized demand curves do provide a useful benchmark although they lie on a different rationale. Indeed, in a centralized market, a sloped demand curve reflects the decreasing probability of black-out as the reserve margin increases. In decentralized capacity markets, LSEs will confront the cost of capacity to their alternative options. Those differ very much from one design to the other: paying the non compliance penalty is commonly considered as the cost of the option, alternatively, one can incentivize changes in load pattern to reduce its portfolio's peak demand as it has been experienced

⁴⁵ According to the Energy Information Administration (EIA), the "reserve margin is $\frac{Capacity - Demand}{Demand}$ ", where "capacity" is the expected maximum available supply and "demand" is expected peak demand" <https://www.eia.gov/>.

⁴⁶ 87.1 GW increased by respectively 15% and 20% leads to capacity targets of 100.1 GW and 104.5 GW.

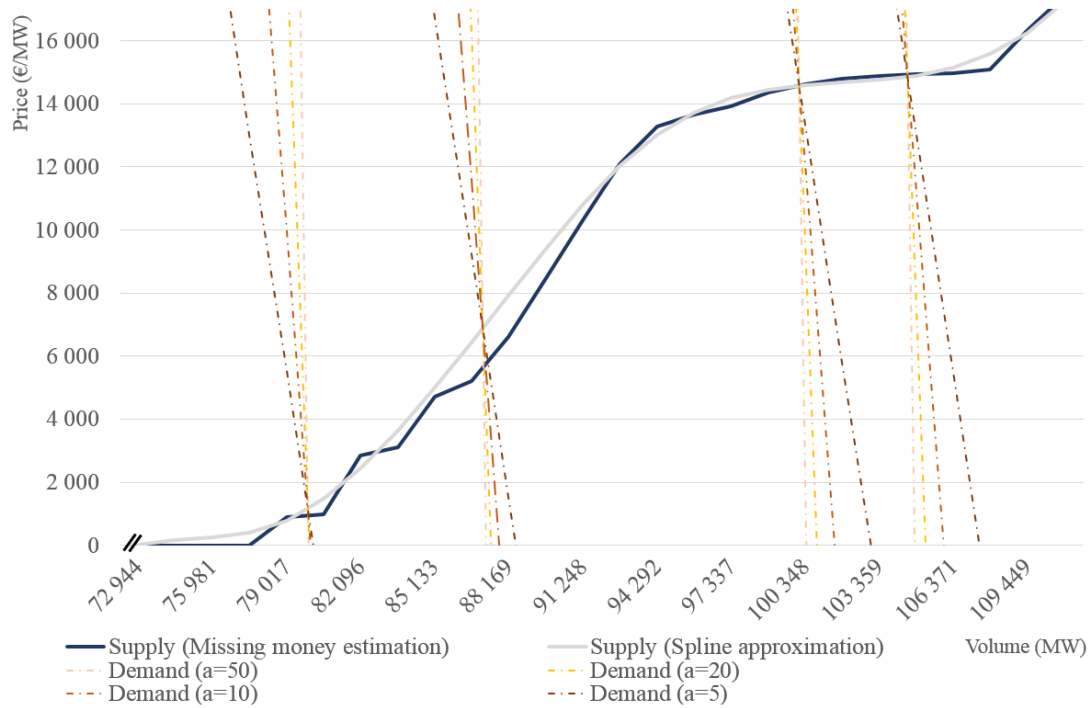


Figure 3.2: Estimated supply and demand curves (no uncertainty) for Germany 2010

in France⁴⁷. However, the continuous discussions with respect to the careful definition of penalties⁴⁸ suggest that they would indeed be designed so private opportunity costs converge towards social opportunity costs. In this case, the aggregated demand curve of a decentralized mechanism could equate a centrally built linear demand curve. We thus turn towards existing centralized mechanisms to get an idea of what could be considered as credible slopes for the aggregated demand. The 2022-2023 demand curve for the UK is piecewise linear, the first segment decreases by around 17£/MW/Year for each additional megawatt procured [DECC, 2014]. On the second segment, the slope is almost twice as steep. Similarly, the NYISO demand curve for the New York Control Area also has a slope around -30\$/MW/Year once converted to comparable values. More constrained areas such as New York City, Long Island, and the "Lower Hudson Valley Zone" (G-J Locality) have much steeper slopes to reflect the high opportunity cost [NYISO, 2018]. Increasing the range to account for possible changes in load pattern, a range of slopes between 5 and 50€/MW/Year decrease in price for each additional megawatt procured is considered. As an example, figure 3.2 represents the various targets considered.

As for the degree of competition, European Commission [2014] states that four major retailers supply the German electricity consumers but households were able to choose

⁴⁷For instance: Grand Lyon (metropolitan area) has investigated process changes in water treatment plants to locate electricity-intensive tasks out of peak hours.

⁴⁸For instance, setting a penalty high enough would increase the slope and reduce the market power problem, however, setting the penalty too high can result too risky, and lead to buyers exiting the market which reduces the competition.

between no less than 65 different retailers in 2011 while the number of retailers operating in the German market was above a thousand (all categories of consumers included). For the sake of the exercise, we will test the preferences of the buyers for respectively four and sixty-five capacity buyers as well as the competitive state.

In the process of designing a capacity market, it is common to organize public consultations to gather insights from the actors. The different combinations of the previously defined parameters can describe distinct market structures, providing the stakeholders with some context to build their preferences. For instance, a steep slope ($a = 50$) suggests either a high penalty for under procurement (capacity market characteristic), or expensive demand response (system characteristics). Similarly, perfect competition is a proxy for a centralized procurement from a benevolent public authority (minimization of the deadweight loss). The intercept reflects the preferred level of reliability. In turn, this determines which owners will be affected by the uncertainty.

3.4.3 Results

The previously defined parameters can be combined to mimic market designs with different features and system specifics: they provide a realistic set up to the model. Each of the twelve resulting designs (three levels of competition and four levels of opportunity cost) represents a credible situation to put into public consultation so to collect preferences with respect to requirement definition. For instance, perfect competition is highly unlikely in the electricity sector, but centralized capacity markets act on behalf of the consumer in a non-strategic way -as if perfectly competitive-. It is thus a good proxy for a centralized mechanism. As discussed in section 3.3.9, perfect information is always welfare-maximizing in perfect competition: a centralized mechanism with *ex post* procurement would not make sense unless the public authority's objective function is not welfare. The preferences under perfect competition are thus displayed as a benchmark so to measure how market power affects preferences as well.

To analyze the actors' preferences, we name the possible sets of preferences with respect to the actors disagreeing with perfect information –*ex ante* requirements (see table 3.6⁴⁹). Consequently, the set of preferences called "Buyer-side" is characterized by all actors but the demand-side preferring full information. "-" pictures the absence of disagreement: all actors prefer full information. Similarly, the "Majority" sees individual capacity owners preferring low information while all aggregated surpluses are all maximized by full information. With this respect, remind that in the capacity market, the size of uncertainty is relatively small compared to the size of the market. It follows that the preferences of the capacity buyers who are certain to sell in any case will dominate the majority-winning case. In the "Owner-side" set, only capacity owners do disagree with full information while in the "Owner and welfare" set, only capacity buyers prefer additional information.

⁴⁹Note that only the thresholds differ in perfect information, but the sets of preferences are the same: we thus use the same name.

| $\eta''(Q)$ | | $\underline{\rho}$ | ρ | $\bar{\rho}$ | $\bar{\bar{\rho}}$ |
|-----------------------------|------------|---------------------------|-----------------|---------------------------|---------------------------|
| Welfare | | $\lambda_W = 1$ | $\lambda_W = 1$ | $\lambda_W = 1$ | $\lambda_W = \frac{1}{2}$ |
| Buyers' Surplus | | $\lambda_S = \frac{1}{2}$ | $\lambda_S = 1$ | $\lambda_S = 1$ | $\lambda_S = 1$ |
| Owners' Profit | | $\lambda_P = 1$ | $\lambda_P = 1$ | $\lambda_P = \frac{1}{2}$ | $\lambda_P = \frac{1}{2}$ |
| Majority-Winning | $m(Q) < 0$ | $\lambda_C = 1$ | $\lambda_C = 1$ | $\lambda_C = \frac{1}{2}$ | $\lambda_C = \frac{1}{2}$ |
| Naming: sets of preferences | | Buyer-side | - | Majority | Owner-side |
| | | Disagree with information | | | |
| | | Owners and welfare | | | |

Table 3.6: Maximizing precision for $n > 1$ and $m(Q) < 0$: Naming the sets of preferences

The size of the uncertainty ($z_h - z_l$) does not affect much preferences since information becomes increasingly valuable for all parties as it increases. It only affects the equilibrium outcomes (see the frame *Accounting for uncertainty* and chapter H for a discussion on the effects of uncertainty). For the sake of simplicity, table 3.7 abstracts from uncertainty ($z_h = z_l$) to depict the preferences of the actors under each of the predefined settings. Synthesizing the information in table 3.7, it is clear that *ex ante* requirements would probably emerge from a "global" consultation. Indeed, public consultations are often conducted for all design features at once i.e. stakeholder are to be consulted on requirement definition at the same time as on other design features such as the non-compliance penalty of the buyers (a), the level of requirement and sometimes even the obligated actors. In this sense, the buyer-side prefers information unless the implicit penalty (a) is low enough. Similarly, the supply-side only prefers *ex post* payments in the limited situation where the supply curve becomes flat⁵⁰ (Q_3^t). If the capacity target has not been announced, they would not take the chance to formulate such preference. The same reasoning applies to the capacity buyers, who are even less likely to benefit from reduced information.

On the contrary, if the bulk of the capacity market has already been defined, as in the model framework, meaning that the opportunity cost and the level of centralization are known as well as the reliability targets, actors can build firm preferences with respect to the requirement definition.

When competition decreases (lower n), capacity buyers are able to use their market power and information becomes more and more valuable as the size of the capacity buyers increases (n decreases). This implies that their preference for a lower degree of information ($\lambda = \frac{1}{2}$) becomes increasingly constrained all things equal: situations where all actors prefer additional information become more probable as n decreases (table 3.7). Namely, a plays a role in preferences: a high slope makes the buyers willing to acquire information. The reason is that when the markdown is low, and when the penalty is high, being aligned with the state of the world matters. On the contrary, when a decreases, the implicit penalty decreases as well, so for a reduced market power (high n), the convexity of the price dominates any other effect in the buyers' preferences similarly as in the perfect

⁵⁰Or alternatively when it increases rapidly, which is not the case here.

| | | $Q_1^t = 79.9 \text{ GW}$ | $Q_2^t = 87.1 \text{ GW}$ | $Q_3^t = 100.1 \text{ GW}$ | $Q_4^t = 104.5 \text{ GW}$ |
|--------------|----------|---------------------------|---------------------------|----------------------------|----------------------------|
| $n = \infty$ | $a = 50$ | - | - | Owner-side | - |
| | $a = 20$ | - | - | Owner-side | - |
| | $a = 10$ | Buyer-side | - | Owner-side | - |
| | $a = 5$ | Buyer-side | - | Owner-side | - |
| $n = 65$ | $a = 50$ | - | - | Owner-side | - |
| | $a = 20$ | - | - | Owner-side | - |
| | $a = 10$ | Buyer-side | - | Owner-side | - |
| | $a = 5$ | Buyer-side | - | Owner-side | - |
| $n = 4$ | $a = 50$ | - | - | Owner-side | - |
| | $a = 20$ | - | - | Owner-side | - |
| | $a = 10$ | - | - | Owner-side | - |
| | $a = 5$ | - | - | Owner-side | - |

Table 3.7: Sensitivity of the form of disagreement to the slope, the competitive equilibrium and the competition

competition case. This explains the antagonism of preferences for the high competition case with a gentle slope in Q_1^t .

In this framework, the role of the implicit penalty and competition appears limited in terms of preference. However, both have a significant effect on surplus allocation and welfare. As the implicit penalty increases, deviations from the competitive equilibrium become more and more costly, reducing the structural under procurement (see Chapter H for a discussion on structural under procurement due to the imperfect competition). As well, the higher the number of buyers, the lower the quantities bought by each of them are, and finally, the lower their individual market power is. In this sense, the total welfare increases with both n and a by way of a reduction of the deadweight loss.

Accounting for uncertainty

Figure I.1 to figure I.16 give further insights on the preferences in table 3.7 by representing the differences in mean quantities and mean prices in full information compared to the no information case ($\lambda = \frac{1}{2}$). When the represented difference is positive, the mean price (resp. quantity) increases with information.

Figure I.1 and figure I.2 illustrate the demand-side disagreement at Q_1^t : capacity buyers use information to reduce the mean quantities procured. However, information leads to an increase in mean prices as in the situation ($a2i$). Unsurprisingly, when the penalty is low, additional information becomes detrimental to their surplus –as the mean price increases with information anyways.

In comparison, when $n = 4$ (always at Q_1^t , see figure I.9 and I.10), the mean price still increases with information. The effect of information on the mean quantity highly depends on demand parameters: when a is high, situation (a1) arises, but a low (a) leads to (a2i). Table 3.7 indicates that information improves the situation of capacity buyers even though the mean quantity might slightly increase in information (when the penalty (a) is high enough). Compared to the case where $n = 65$, the increase of the mean price in information is decreasing more when (a) decreases. It means that when (a) decreases, the market power in the case with information do increase. It is sufficient to make buyers prefer information (with respect to the situation where $n = 65$). Thus, the penalty may have a different impact on the equilibrium outcomes (and the preferences), according to the market structure (i.e. level of competition). As the mean price increases in precision with both market structures, capacity owners prefer information.

At Q_2^t however (figure I.3, I.4, I.11 and I.12), both the mean price and the mean quantity increase with information (case (a1)) whatever the level of competition. Again, capacity owners always prefer information in this situation. With respect to capacity buyers, they prefer information. Contrary to Q_1^t , the increase of the mean price in information increases when (a) decreases. Thus, the effect of more information does not always multiply the negative effect of a lower penalty on the mean prices and quantities (as the structural under procurement increases when (a) decreases).

At Q_3^t , capacity buyers prefer information as it allows an important decrease in the mean price while the mean quantity decreases ($n = 4$, figure I.13 and I.14) (case (b2)) or even increases slightly ($n = 65$, figure I.5 and I.6) (case (b1ii)). This situation creates a clear loss for capacity owners who then prefer no information.

At Q_4^t (figure I.7, I.8, I.15 and I.16), the mean quantities are decreasing in information while prices do increase (case (a2i)). Better alignment with the state of the world is enough to make capacity buyers gain from information in this situation. Naturally, capacity owners are satisfied with the resulting increase of the mean price.

3.4.4 Discussion

In our framework, disagreement between profit-maximizing and majority-winning criteria is improbable. Indeed, if the price increases with information precision (so the majority criterion selects full information), then the profit is likely to increase as well since the marginal effect on quantity is much lower than the marginal increase price. When such a disagreement exists locally, it corresponds to an unstable situation, given the uncertainty. Indeed, the "Majority" type of disagreement is characterized by a price decreasing in information precision while the profit is still increasing. However, it is only natural that the variation of profit closely follows the variation of price when information pre-

cision increases. It follows that between the situation where no party disagrees (profit and price increasing in information) and the "Owner-side" type of disagreement, only a small interval will allow price and profits to evolve in opposite directions when information increases. For instance, when $n = 65$ and $a = 5$, disagreement between capacity owners appears when the demand curve crosses the supply curve in the rather small interval $Q^t \in [101940, 101960]$. This represents less than 0.2% of the total capacity to be procured at this point. In comparison, the French TSO, RTE, considers a 2% uncertainty between its high and low scenario [RTE, 2015]. Consequently, the "Majority" type of disagreement is empirically more of a buffer zone between capacity owners preferring full information towards a preference for reduced information as the markdown becomes increasingly convex (or less concave) –compared to the convexity of the supply function–.

Finally, the "Owner and welfare" type of disagreement does not appear in the case study. It is also an intriguing result from the model: how could a central planner prefer low information as a design? Once again, the answer lies in the market power. From a welfare perspective, it might be preferable to have lower information in order to prevent the oligopsony from abusing its market power by buying too little capacity even from a welfare perspective. More precisely, for a central (welfare-maximizing) authority to prefer a lower precision, the supply curve behavior needs to be radically changed. In the convex case, the supply function should be increasing more than exponentially. In this situation, a small change in quantities allows for great variations in prices, which greatly benefits the oligopsony under perfect information: the informational gains of the capacity buyers are lower than the respective losses of the capacity owners. However, this situation is unlikely to happen with a competitive behavior from the existing capacity owners as pictured here. Indeed, the curve of stacked profit gaps is rather smooth because they already recover at least their marginal cost from the energy market. Nevertheless, the supply curve estimated in section 3.4.1 abstracts from possible new entrants who would need to recover their investment costs in addition to fixed ones: if investments were to be necessary to comply with the reliability target, the end of the competitive supply curve might become very steep since those units would also need to recover investment annuity costs. Only in this case, or in a market with specific supply-side strategic behavior could the "Owner and welfare" type of disagreement emerge.

However, those results remain indicative as not all the assumptions are empirically verified (or verifiable). Mainly, the shape of the supply curve is deemed independent of the signal, which reduces the range of possible strategic behaviors. In addition, the only uncertainty in the model regards the level of required capacity, meaning that all remaining information is public and common to all actors (shape of the supply curve, the elasticity of the marginal value and the number of market participants). Those assumptions are obviously little realistic: when a public authority wants to design a capacity market, she does not benefit from such information yet. Only the first market clearings will convey accurate information on the supply and demand. In the meanwhile, it still needs to decide what design to implement. For all those reasons, a theoretical case study is preferred to

an actual empirical application based on publicly available auction data. This chapter provides insights on actors' preferences in terms of requirement definition under different options with respect to the other design features. This echoes the stakeholders' response to the British public consultation on the electricity market reform in 2011 [DECC, 2011]: it is complex to discuss implementation features without a view on the global design.

3.5 Conclusion

In this chapter, we investigate information disclosure in capacity remuneration mechanisms (CRMs). We argue that the precision of the available information is embedded in the design itself. By tailoring CRMs in different ways, the public authority controls the amount and accuracy of the information revealed by the market and consequently affects the agents' forecast errors on their optimal level of capacity needed. By mostly choosing forward capacity markets, public authorities around the world limit the ability of LSEs to predict their future capacity demand efficiently. To hedge for the lead time related uncertainties, the capacity requirements are more or less precisely stated at the moment of procurement. The UK or eastern US type of centralized procurement leaves no doubt on the aggregated level of demand: the demand curve presented at the auction is the legal capacity requirement. The state of the world is known, the requirements -and thus procurements- are either high or low. On the contrary, the former MISO or former PJM as well as the French mechanism leave the LSEs estimate and secure their load in a decentralized way. Where *ex ante* requirements in a perfect competition framework would resume to a centralized procurement, *ex post* requirements penalize forecast errors. This represents an uncertainty around the state of the world that cannot be fully hedged. In other words, the French mechanism does not allow full information disclosure as its counterparts do. If the centralized versus decentralized discussion is recurrent in the literature, this CRM feature is rarely disentangled from the timing of requirements (*ex ante* vs. *ex post*) which does affect risk sharing and incentives [CIGRE, 2016].

Symmetrically to Roy et al. [2019], we model heterogeneous price taker capacity owners and homogeneous buyers competing *a la Cournot* under uncertainty on their level of capacity obligation. We investigate both the effect of a decentralized capacity mechanism under imperfect competition on the equilibrium and the actors preferences in terms of information disclosure (requirement definition). The reference model is adapted to capacity markets by considering an oligopsony – instead of an oligopoly. By introducing a decreasing slope for the buyers' marginal value –instead of a constant marginal cost–, we can analyze the slope of the marginal value curve in terms of implicit penalty. It represents the cost of not procuring enough capacity like the legal penalty or the ability to release Demand Response (DR) in the short term. Whereas Roy et al. [2019] was focused on preferences, we add results that deal with the industrial organization. For this purpose, we use the function $\eta(Q, n)$ introduced to enhance the influence of the market structure and asymmetric incentives on the equilibrium outcomes. It is equivalent to the

markdown at the equilibrium. Naturally, results indicate that the aggregated quantities procured increase with the number of buyers. As a consequence, the decentralized capacity mechanism will tend to under procure capacity compared to a benevolent central planner (perfect competition case). In practice, this means that if the parameters of the market (i.e. the penalty and the reward) are not adjusted accordingly, both price and quantities will be unnecessarily low compared to the optimal situation from the welfare point of view.

In line with Roy et al. [2019], we consider 3 decision criteria: the capacity buyers' surplus and capacity owners' profit as well as the majority criterion. We add the welfare criterion since it is usually the objective of the public authority to maximize the welfare. The majority criterion mimics the preferences that could be expressed by market participants during the consultations organized previous to the regulation change. Indeed, regulation should seek welfare maximization, and real-life imperfect information makes actors' preferences a good proxy. For homogeneous buyers, their individual preference will always be aligned with the surplus maximizing criterion. However, heterogeneous capacity owners' preferences might differ at the individual level expressed in a consultation process. The latter indeed gains relevance with the growing competition in electricity markets and the raising concern about plants' profitability: each plant is now individually required to be profitable and cross-unit subsidies abandoned. In this context, reasoning in survival terms brings out interesting considerations. Consistently with the diversity of capacity market designs in terms of requirement definition, the model introduces cases where buyers and owners agree as well as the reverse. As in the reference model, we have found that the preferences about the information disclosure depend mainly on the supply curve. Following the economic intuition, results show that full information is mostly preferred. Nonetheless, conflicts between the categories of agents may emerge. We highlight the preferences in terms of precision for each group under the assumption that the public authority might be influenced by one or the other depending on its utility (mission of public interest) as much as the efficiency with which they make their preferences heard. Antagonism amongst capacity owners might emerge when the interests of the owners guaranteed to sell in any case differ from the interest of the owners affected by the uncertainty. When the sum of people in the first group is much higher than the sum of people in the second group, the aggregation of private preferences may not be profit-maximizing in theory. Besides, even without considering market power abuse from the supply-side, we have found that information can be detrimental to the welfare. In addition, letting the owners strategically use information would probably increase the number of cases where the welfare decreases with precision.

In terms of CRMs, this chapter sheds light on the market power of the demand-side. In this simple framework, without risk aversion, we show that *ex post* requirements might be preferred, even by the buyers' side (whose the surplus is state-contingent). However, in this model, a consensus for no information is never generated. Thus, retaining information is always detrimental to at least one side. We show that no information can be welfare

improving when the markdown increases quickly with information (relative to the price function). A case study is built based on German data (2010) to develop a better understanding of the model implications. For tractability reasons, capacity owners are assumed to bid competitively their profitability gap. Then, various market structures in terms of demand level, slope or competition are applied against the supply curve to determine the actors' preferences under different circumstances. Results show that information becomes more valuable for LSEs as their number decreases. Indeed, as the number of capacity buyers and the implicit penalty decrease, the markdown mostly drives the equilibrium decisions and consensus towards full information becomes more probable. Naturally, with respect to equilibrium quantities, under procurement tends to increase as the number of capacity buyers decreases. A reduction in the implicit penalty further increases market power. When the market power is important, the level of under procurement can be such that SoS would be endangered under any structure of information. This result sheds light on the importance of setting an adequate penalty. Indeed, the implicit penalty drives not only the preferences, but also the market power and the optimality of market outcomes from a welfare perspective.

Fortunately for policy makers, results suggest the efficiency of consultations as a way to uncover actors' preferences: the majority type disagreement appears empirically unlikely. In addition, the welfare type of disagreement would not naturally occur in real capacity markets. Indeed, for information to be detrimental to welfare, the curvature of the supply function has to be radically modified. This situation is improbable in capacity markets if only existing units compete. However when new units are needed, the supply curve can be quickly increasing at its end. Indeed, they might need to recover much more from the capacity market.

Setting aside the risks related to market power abuse from the demand-side, decentralizing markets with *ex post* requirements are often presented as a way to increase system reliability at a limited cost due to the accurate capacity cost allocation [RTE, 2014; Woodhouse, 2016]. By making capacity buyers accountable for what they buy, the classical "skin in the game" argument may play an important role. This argument is empirically nuanced by the actual hedging LSEs benefit from: demand uncertainty is known to average out with aggregation, but end consumers have their hands on their load pattern. If LSEs are not able to better forecast their peak demand than the central authority, then shifting uncertainty on LSEs becomes only risk sharing, especially if their load management possibilities are limited. In this framework, further research on LSEs risk aversion is needed. Mainly, two types of risk aversion can be identified: (i) the probability of being wrong is indeed accounted for in this model as it relates to the value of information. It only affects $\mathbb{E}(Z|S)$. On the contrary, (ii) the relative cost of being wrong does affect the slope of the marginal value a that is considered as exogenous in our framework. If LSEs are able to accurately forecast their peak demand by way of DR, then accurate cost allocation as in *ex post* decentralized mechanisms does provide accurate incentive to lower peak consumption. This discussion relates to Crew and Kleidorfer [1976] consideration:

"Rationing costs occur with stochastic demand whenever capacity is exceeded. These occur because it is not possible costlessly to rank consumers according to their willingness to pay and because there are added costs to the utility in actually performing the operation of rationing. In addition, there may be added production costs [...] of running to the limit of total capacity. There is no reason to suppose that such costs will on the average decrease as the amount by which demand exceeds capacity increases. Indeed, it is likely that such costs will increase at an increasing rate, because as the deficit of capacity increases the utility is more likely to cut off consumers with higher valuation."

Crew and Kleidorfer [1976]

Until recently, this statement was true and counting on DR was for dreamers. This is why former decentralized mechanisms as MISO or PJM relied on *ex ante* requirements (second-best capacity cost allocation). However, technological improvements allow DR units to be valued as SoS tools. Implementing real time metering at large scale would partially solve the two problems mentioned by Crew and Kleidorfer [1976] as it means inexpensive ranking of consumers and reduced costs of performing the operation of rationing. In decentralized mechanisms with *ex post* requirements, DR can be valued for what it is in the demand-side. However, this requires that each actor is accountable for its consumption pattern with respect to SoS objective (accurate cost allocation and real-time metering). A critical limit to this incentive is that it represents a rather short term solution: because of the interrelations with the electricity markets, peak shaving tends to push units out of the market in the long run, which only delays SoS concerns (until the residual load is rather flat).

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Appendices

Appendix D

Equilibrium Conditions

Let q_j be the capacity demanded by the buyer j and $Q = \sum_{i=1}^n q_i$ the total bought capacity. The individual buyers' surplus is naturally defined as the surface between their individual demand curve and the price: $S(q_j) = \int_0^{q_j} D_j^{-1}(x) - F(Q)dx = \int_0^{q_j} \mathbb{E}(Z|s) - na x - F(Q)dx$.

Maximizing with respect to q_i , with \bar{Q} being the quantity bought by all the other buyers ($Q = \bar{Q} + q_j$), we derive the First Order Conditions FOC:

$$\begin{aligned} \frac{\partial S(q_j)}{\partial q_j} = 0 &\Leftrightarrow \mathbb{E}(Z|s) - na \times q_j - \frac{\partial F(q_j + \bar{Q})}{\partial q_j} q_j - F(q_j + \bar{Q}) = 0 \\ &\Leftrightarrow \mathbb{E}(Z|s) = \left(\frac{\partial F(q_j + \bar{Q})}{\partial q_j} q_j + F(q_j + \bar{Q}) + na \times q_j \right) \quad (\text{FOC}) \end{aligned}$$

Let $Q^*(\mu_h)$ and $q^*(\mu_h)$ be the equilibrium quantities when the buyers have the belief that $\mathbb{P}(Z = z_h) = \mu_h$. Since we only consider symmetric equilibria: $Q^*(\mu_h) = \sum_{j=1}^n q^*(\mu_h) = nq^*(\mu_h)$. If there is no ambiguity, we note for the sake of simplicity $Q^* = Q^*(\mu_h)$ and $q^* = q^*(\mu_h)$. FOC becomes:

$$\underbrace{\mathbb{E}(Z|s) - na \times q^*}_{\text{Marginal Value } (V(q^*, n))} = \underbrace{\left(\frac{\partial F(nq^*)}{\partial q} q^* + F(nq^*) \right)}_{\text{Marginal Cost } (C(q^*, n))} \quad (\text{sFOC})$$

We implicitly differentiate sFOC with respect to the precision λ :

$$\frac{dq^*}{d\mu_h} = \frac{\frac{\partial \mathbb{E}(Z|s)}{\partial \mu_h}}{\frac{\partial (\frac{\partial F(nq^*)}{\partial q} q^* + F(nq^*) + na)}{\partial q^*}}$$

And we note the following function:

$$L_i(q^*, n) = \frac{\partial F(nq^*)}{\partial q} q^* + F(nq^*) + na \times q^*$$

We obtain the next equilibrium condition with respect to μ_h , with $\zeta = z_h - z_l$:

$$\frac{d q^*}{d \mu_h} = \frac{\zeta}{L'(Q^*)}$$

Appendix E

Proofs

Theorem 1. Under Assumption 1, there exists a unique symmetric equilibrium to the Cournot Oligopsony with n buyers.

Proof. The First Order Condition FOC for any buyer j gives:

$$\frac{\partial S(q_j)}{\partial q_j} = 0 \Leftrightarrow \mathbb{E}(Z|S) - an \times q_j - F(Q) - \frac{\partial F(Q)}{\partial q_j} q_j = 0$$

Assume a function $g(x_i, X) = \mathbb{E}(Z|S) - anx_i - F(X) - F'(X)x_i$, defined in $\mathbb{R} \times [0, \xi]$ where the bound ξ is such that $F(\xi) = z_h + \epsilon$ with $\epsilon > 0$ and bounded.

Then a Cournot equilibrium must satisfy:

$$g(q_i, X) \leq 0, \quad q_i \geq 0, \quad g_i(q_i, X)q_i = 0 \quad \forall i = 1 \dots n \quad (\text{Optimality})$$

$$X = \sum_{i=1}^n q_i \quad (\text{Feasibility})$$

Note that g is continuous and twice-continuously differentiable. Furthermore g is decreasing in x_i , since the partial derivative in x_i is bounded away from 0: $\frac{\partial g(x_i, X)}{\partial x_i} = -(an + F'(X)) < 0$. Then, there exists a unique $x_i(X)$ such that $g(x_i(X), X) = 0$. The implicit function theorem is then applicable and $x_i(X)$ must be unique for each $X \in [0, \xi]$. Since this is true for a neighborhood of each X , $x_i(X)$ must be a continuous function. Finally, the Optimality condition has a unique solution:

$$q_i(X) = \max[0, x_i(X)] \quad \forall X \in [0, \xi]$$

We must show that the Feasibility condition has at least one solution. One can check that $q_i(X)$ and then $Q(X) = \sum_{i=1}^n q_i(X)$ are continuous on $[0, \xi]$. By definition, $q_i(X) \geq 0 \forall X \in [0, \xi]$ and $q_i(\xi) = 0$. Then, by continuity, and since $Q(0) \geq 0$ and $Q(\xi) = 0$, there is at least one $X \in [0, \xi]$ such that the Feasibility condition is met: $X = Q(X)$. Then a solution to both conditions is such that: $\bar{X} = Q(\bar{X})$ with $Q(\bar{X}) = \sum_{i=1}^n q_i(\bar{X})$.

Set $q_i = \max[0, \varphi(Q)]$. By the implicit function theorem on $g(q_i, Q) = 0$, we can write when $q_i > 0$ ¹:

$$\frac{d q_i}{d Q} = -\frac{F''(Q)q_i + F'(Q)}{an + F'(Q)}$$

Since $Q = \sum_{i=1}^n q_i$,

$$Q' = \sum_{i=1}^n \frac{q_i}{d Q}$$

$$Q' = -\frac{F''(Q)Q + nF'(Q)}{an + F'(Q)} < 1 \text{ if and only if } F''(Q)Q > -[(n+1)F'(Q) + an]$$

As already stated, $Q \geq 0$, and there is exactly one Cournot equilibrium such that $\bar{X} = Q(\bar{X})$ under Assumption 1. ■

Lemma 1. Under Assumption 1, for $s = s_h$ (resp. $s = s_l$), the equilibrium quantities increase (resp. decrease) with the belief μ_h . Furthermore, $\mathbb{E}(Q^*)$ is increasing (resp. decreasing) with respect to λ if $L(Q)$ is concave (resp. $L(Q)$ is convex). Equivalently, $\mathbb{E}(Q^*)$ is increasing (resp. decreasing) if $QF'''(Q) + (n+2)F''(Q) < 0$ (resp. $QF'''(Q) + (n+2)F''(Q) > 0$).

Proof. Assume the objective function of the public authority is the mean quantity. Under which condition should the public authority disclose information to maximize its objective function? We want to establish that if $(Q^*(\mu_h))$ is convex, $\mathbb{E}(Q^*)$ is maximal when $\lambda = 1$. When $\lambda = 1$, information being perfect, buyers believes with probability 1 that the state of the world is either h , either l . We want to show that $\forall (\mu_h(s_l), \mu_h(s_h))$ with $\mu_h(s_h) \in [\mu_0, 1]$, and $\mu_h(s_l) \in (0, \mu_0]$ (with $\bar{\lambda} < 1$ the precision giving $\mu_h(s_l), \mu_h(s_h)$):

$$\begin{aligned} & \mathbb{P}(S = s_h | \lambda = 1)Q^*(1) + \mathbb{P}(S = s_l | \lambda = 1)Q^*(0) > \mathbb{P}(S = s_h | \lambda = \bar{\lambda})Q^*(\mu_h(s_h)) \\ & \quad + \mathbb{P}(S = s_l | \lambda = \bar{\lambda})Q^*(\mu_h(s_l)) \\ \Leftrightarrow & \mu_0 Q^*(1) + (1 - \mu_0)Q^*(0) > \frac{\bar{\lambda}\mu_0}{\mu_h(s_h)}Q^*(\mu_h(s_h)) + \frac{(1 - \bar{\lambda})\mu_0}{\mu_h(s_l)}Q^*(\mu_h(s_l)) \end{aligned}$$

We know, by convexity of $Q^*(\mu_h)$, that:

$$Q^*(1) - Q^*(0) > \frac{Q^*(\mu_h(s_h)) - Q^*(0)}{\mu_h(s_h)} > \frac{Q^*(\mu_h(s_l)) - Q^*(0)}{\mu_h(s_l)}$$

Then, $\forall \alpha \in [0, 1]$,

$$Q^*(1) - Q^*(0) > \alpha \frac{Q^*(\mu_h(s_h)) - Q^*(0)}{\mu_h(s_h)} + (1 - \alpha) \frac{Q^*(\mu_h(s_l)) - Q^*(0)}{\mu_h(s_l)}$$

¹One can easily remark that for any $z_h, z_l > 0$, if $Q = 0$, then $x_i(Q) > 0$, which shows that 0 is not an equilibrium quantity.

Recalling that $\bar{\lambda} \frac{\mu_0}{\mu_h(s_h)} + (1 - \bar{\lambda}) \frac{\mu_0}{\mu_h(s_l)} = 1$, we can write:

$$\begin{aligned} \mu_0(Q^*(1) - Q^*(0)) &> \alpha \frac{\mu_0}{\mu_h(s_h)} (Q^*(\mu_h(s_h)) - Q^*(0)) + \\ &\quad (1 - \alpha) \frac{\mu_0}{\mu_h(s_l)} (Q^*(\mu_h(s_l)) - Q^*(0)) \\ \Leftrightarrow \mu_0(Q^*(1) - Q^*(0)) &> \bar{\lambda} \frac{\mu_0}{\mu_h(s_h)} Q^*(\mu_h(s_h)) + (1 - \bar{\lambda}) \frac{\mu_0}{\mu_h(s_l)} Q^*(\mu_h(s_l)) - Q^*(0) \\ \Leftrightarrow \mu_0 Q^*(1) + (1 - \mu_0) Q^*(0) &> \bar{\lambda} \frac{\mu_0}{\mu_h(s_h)} Q^*(\mu_h(s_h)) + (1 - \bar{\lambda}) \frac{\mu_0}{\mu_h(s_l)} Q^*(\mu_h(s_l)) \end{aligned}$$

If the function $Q^*(\mu_h)$ is concave, analog computations show that the mean quantity is maximal when $\lambda = \frac{1}{2}$. ■

Lemma 2. $\mathbb{E}(P^*)$ is increasing (resp. decreasing) with respect to λ if the price is convex in the belief μ_h , i.e. if $\frac{F''(Q)}{F'(Q)} > \frac{L''(Q)}{L'(Q)}$ (resp. $\frac{F''(Q)}{F'(Q)} < \frac{L''(Q)}{L'(Q)}$).

$\mathbb{E}(P)$ is increasing (resp. decreasing) if:

$$\eta''(Q) < (>) \frac{F''(Q)}{F'(Q)} (\eta'(Q) + an) \equiv \rho$$

Proof. We want to show that $\frac{F''(Q)}{F'(Q)} > (<) \frac{L''(Q)}{L'(Q)} \Leftrightarrow \eta''(Q) < (>) \rho$. Note that:

$$\begin{aligned} \frac{F''(Q)}{F'(Q)} &> \frac{L''(Q)}{L'(Q)} \\ \Leftrightarrow QF'''(Q) + (n+2)F''(Q) &< (QF''(Q) + (n+1)F'(Q) + an) \frac{F''(Q)}{F'(Q)} \\ \Leftrightarrow QF'''(Q) + 2F''(Q) &< (QF''(Q) + F'(Q) + an) \frac{F''(Q)}{F'(Q)} \\ \Leftrightarrow \eta''(Q) &< \frac{F''(Q)}{F'(Q)} (\eta'(Q) + an) \end{aligned}$$
■

Corollary 1. $\mathbb{E}(P^*)$ is increasing (resp. decreasing) if:

$$\begin{cases} \text{if } F'' > 0, a > (<) \frac{F'(Q)\eta''(Q)}{nF''(Q)} - \frac{\eta'(Q)}{n} \\ \text{if } F'' < 0, a < (>) \frac{F'(Q)\eta''(Q)}{nF''(Q)} - \frac{\eta'(Q)}{n} \end{cases}$$

Proof. From Lemma 2, $\mathbb{E}(P^*)$ is increasing if:

$$\begin{aligned} \eta''(Q) &< \frac{F''(Q)}{F'(Q)} (\eta'(Q) + an) \\ \Leftrightarrow anF''(Q) &> F'(Q)\eta''(Q) + \eta'(Q)F''(Q) \\ \Leftrightarrow \begin{cases} \text{if } F'' > 0, a > \frac{F'(Q)\eta''(Q)}{nF''(Q)} - \frac{\eta'(Q)}{n} \\ \text{if } F'' < 0, a < \frac{F'(Q)\eta''(Q)}{nF''(Q)} - \frac{\eta'(Q)}{n} \end{cases} \end{aligned}$$
■

Lemma 3. If $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$, then individual profits are non decreasing and aggregated profit increases with the precision λ of the signal.

Proof. We note $Q = Q^*$ for simplicity. Assume $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$. For owners with bid under $F(Q(\mu_h = 0))$, i.e. the ones that always sell, the expected profit naturally increases as well with respect to λ . Thus, they prefer $\lambda = 1$. Note also that owners with bids above $F(Q(\mu_h = 1))$, i.e. the ones that never sell, do not see their situation evolve.

Consider now that the precision is set to a given $\tilde{\lambda} \in [\frac{1}{2}, 1)$, giving two beliefs according to the signal received: $\mu_h(s_h)$ and $\mu_h(s_l)$. Owners with bids above $F(Q(\mu_h(s_h)))$ but below $F(Q(1))$, do not sell when the precision is set at $\tilde{\lambda}$ whilst they would sell if λ was set to 1 when the state of the world is high. All of them see their expected profit increase with respect to λ .

It is still true for owners whose bid is above $F(Q(\mu_h(s_l)))$ (but below $F(Q(\mu_h(s_h)))$). They sell only if the signal is high. Then, if there is an increase in $F(Q(\mu_h(s_h)))$ their individual profits increase. We show in the next step why they do not prefer a decrease in λ (i.e. the possibility to sell in both cases).

As well, for owners with bids included in $[F(Q(\mu_h = 0)), F(Q(\mu_h(s_l)))]$, an ambiguity may arise because their quantity sold may be reduced when λ increases. Initially, they sell in both cases. However, if $\lambda = 1$, they do not sell anymore when the signal is low. Their expected profit with bid b_i in first case is:

$$\begin{aligned} \Pi(\tilde{\lambda}) &= \mathbb{P}(S = s_h | \lambda = \tilde{\lambda}) F(Q(\mu_h(s_h))) + \mathbb{P}(S = s_l | \lambda = \tilde{\lambda}) F(Q(\mu_h(s_l))) - b_i \\ &= \frac{\tilde{\lambda} \mu_0}{\mu_h(s_h)} F(Q(\mu_h(s_h))) + \frac{(1 - \tilde{\lambda}) \mu_0}{\mu_h(s_l)} F(Q(\mu_h(s_l))) - b_i \end{aligned}$$

Their expected profit in second case is:

$$\Pi(\lambda = 1) = \mu_0 [F(Q(1)) - b_i]$$

By assumption, we know that $\mathbb{E}(P(\tilde{\lambda})) < \mathbb{E}(P(\lambda = 1))$ for any $\tilde{\lambda} \in [\frac{1}{2}, 1)$.

Then, since $F(Q(0)) < b_i$ for any owner i considered here:

$$\begin{aligned} &\mathbb{E}(P(\tilde{\lambda})) < \mathbb{E}(P(\lambda = 1)) \\ \Leftrightarrow &\frac{\tilde{\lambda} \mu_0}{\mu_h(s_h)} F(Q(\mu_h(s_h))) + \frac{(1 - \tilde{\lambda}) \mu_0}{\mu_h(s_l)} F(Q(\mu_h(s_l))) < \mu_0 F(Q(1)) + (1 - \mu_0) F(Q(0)) \\ \Leftrightarrow &\frac{\tilde{\lambda} \mu_0}{\mu_h(s_h)} F(Q(\mu_h(s_h))) + \frac{(1 - \tilde{\lambda}) \mu_0}{\mu_h(s_l)} F(Q(\mu_h(s_l))) - (1 - \mu_0) F(Q(0)) - \mu_0 b_i < \\ &\mu_0 F(Q(1)) - \mu_0 b_i \\ \Rightarrow &\frac{\tilde{\lambda} \mu_0}{\mu_h(s_h)} F(Q(\mu_h(s_h))) + \frac{(1 - \tilde{\lambda}) \mu_0}{\mu_h(s_l)} F(Q(\mu_h(s_l))) - b_i < \mu_0 [F(Q(1)) - b_i] \\ \Leftrightarrow &\Pi(\tilde{\lambda}) < \Pi(\lambda = 1) \end{aligned}$$

Therefore, each individual profit increases or stays null when information gains precision. Immediately, the aggregated profit increases with the precision since it is the sum of the individual profits and since there are more owners selling their capacity even if the mean quantities may decrease with precision. ■

Proposition 1. With a monopsony, i.e. $n = 1$, the buyers' surplus increases with information precision (increases in λ). The monopsony shall always prefer $\lambda = 1$.

Proof. We first write the expected surplus:

$$\begin{aligned} S(Q_S) &= \int_0^{Q_S} \mathbb{E}(Z|S) - ax - F(Q_S) dx \\ \Rightarrow S(Q^*(\mu_h)) &= Q^*(\mu_h) \left(\mu_h \zeta + z_l - \frac{1}{2} a Q^*(\mu_h) - F(Q^*(\mu_h)) \right) \end{aligned}$$

Since $\mathbb{E}(Z|S) = \mu_h z_h + (1 - \mu_h) z_l = \mu_h \zeta + z_l$ and the derivative of $-\frac{1}{2} ax^2$ is $-ax$.

Then, we can deduce the derivative with respect to μ_h when there is just one buyer:

$$\begin{aligned} \frac{\partial S(Q^*(\mu_h))}{\partial \mu_h} &= \frac{\partial Q^*(\mu_h)}{\partial \mu_h} \underbrace{(\mu_h \zeta + z_l - a Q^*(\mu_h) - F(Q^*(\mu_h)) - F'(Q^*(\mu_h)) Q^*(\mu_h))}_{=0 \text{ if sFOC}} \\ &\quad + Q^*(\mu_h) \zeta \\ \Rightarrow \frac{\partial S(Q^*(\mu_h))}{\partial \mu_h} &= Q_h^*(\mu_h) \zeta \quad (\text{Monopsony's Surplus Derivative}) \end{aligned}$$

Then, $\frac{\partial^2 S(Q^*(\mu_h))}{\partial \mu_h^2} = \frac{n \zeta^2}{L'(Q_h^*(\mu_h))} > 0$ ■

Proposition 2. If $n > 1$, $\mathbb{E}(S(Q^*))$ is increasing (resp. decreasing) with respect to λ if the surplus is convex in the belief μ_h , i.e. if $(1 - \frac{(n-1)F'(Q)}{L'(Q)})Q$ is increasing (resp. decreasing). Then, in the first case, the surplus maximizer precision is $\lambda_S = 1$, and in the second case $\lambda_S = \frac{1}{2}$. As well, the surplus is increasing (resp. decreasing) with information precision if:

$$\eta''(Q) > (<) \rho - \frac{L'(Q)(L'(Q) - (n-1)F'(Q))}{(n-1)QF'(Q)} \equiv \underline{\rho}$$

Proof. By dividing the total surplus (see the proof of Proposition 1) by n , and by writing the surplus as a function of individual quantities $\left(q = q^*(\mu_h) = \frac{Q^*(\mu_h)}{n}\right)$: the expected surplus for any buyer j at the equilibrium is:

$$S_j(q) = q \left(\mu_h \zeta + z_l - \frac{1}{2} a n q - F(nq) \right)$$

By differentiating with respect to μ_h :

$$\begin{aligned}\frac{\partial S_j(q)}{\partial \mu_h} &= \frac{dq}{d\mu_h} (\mu_h \zeta + z_l - anq - F(nq) - nqF'(nq)) + q\zeta \\ &= -\frac{dq}{d\mu_h} ((n-1)qF'(nq)) + q\zeta \\ &= q\zeta \left(1 - (n-1) \frac{F'(nq)}{L'(nq)} \right)\end{aligned}$$

Differentiating up to the order two:

$$\begin{aligned}\frac{\partial^2 S_j(q)}{\partial \mu_h^2} &= \frac{\zeta}{d\mu_h} \left(\left(1 - (n-1) \frac{F'(nq)}{L'(nq)} \right) - (n-1)nq \left(\frac{F''(nq)L'(nq) - F'(nq)L''(nq)}{L'(nq)^2} \right) \right) \\ &= \frac{\zeta}{L'(Q)^3} (L'(Q)(L'(Q) - (n-1)F'(Q)) - (n-1)Q(F''(Q)L'(Q) - F'(Q)L''(Q)))\end{aligned}$$

This second derivative is positive if and only if, $\forall Q = Q^*(\mu_h)$ with $\mu_h \in [0, 1]$:

$$\begin{aligned}F'(Q)L''(Q) + \frac{L'(Q)(L'(Q) - (n-1)F'(Q))}{(n-1)Q} &> F''(Q)L'(Q) \\ \Leftrightarrow QF'''(Q) + 2F''(Q) + nF''(Q) &> F''(Q)L'(Q) - \frac{L'(Q)(L'(Q) - (n-1)F'(Q))}{(n-1)QF'(Q)} \\ \Leftrightarrow \eta''(Q) &> \frac{F''(Q)(QF''(Q) + (n+1-n)F'(Q) + an)}{F'(Q)} - \frac{L'(Q)(L'(Q) - (n-1)F'(Q))}{(n-1)QF'(Q)} \\ \Leftrightarrow \eta''(Q) &> \rho - \frac{L'(Q)(L'(Q) - (n-1)F'(Q))}{(n-1)QF'(Q)}\end{aligned}$$

■

Corollary 2. When $(n-1)(QF''(Q) + F'(Q))^2 - 4QF'(Q)(QF'''(Q) + (n+2)F''(Q)) = (n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q) \leq 0$ the surplus is increasing with information precision.

Note

$$a_{1s} = -\frac{\sqrt{(n-1)}\sqrt{(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - \frac{F'(Q) - QF''(Q)}{2}$$

and

$$a_{2s} = \frac{\sqrt{(n-1)}\sqrt{(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - \frac{F'(Q) - QF''(Q)}{2}$$

When $(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q) > 0$ the surplus is increasing (resp. decreasing) with information precision if:

$$\begin{cases} \text{in case where } a_{2s} < 0 \\ \text{in case where } a_{2s} > 0 \text{ and } a_{1s} < 0, \text{ if } a > (<) a_{2s} \\ \text{in case where } a_{1s} > 0, \text{ if } a > a_{2s} \text{ or } a < a_{1s}, (\text{ if } a_{1s} < a < a_{2s}) \end{cases}$$

Proof. By the proof of Proposition 2, we know that the surplus is increasing with information precision if:

$$F'(Q)L''(Q) + \frac{L'(Q)(L'(Q) - (n-1)F'(Q))}{(n-1)Q} - F''(Q)L'(Q) > 0$$

$$\Leftrightarrow \left(F'(Q)L''(Q) + \frac{L'(Q)(L'(Q) - (n-1)\eta'(Q))}{(n-1)Q} > 0 \right)$$

Assume $(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q) \leq 0$. Then,

$$F'(Q)L''(Q) \geq \frac{(n-1)\eta'(Q)^2}{4Q}$$

Thus,

$$\begin{aligned} & F'(Q)L''(Q) + \frac{L'(Q)(L'(Q) - (n-1)\eta'(Q))}{(n-1)Q} \\ & > \frac{(n-1)\eta'(Q)^2}{4Q} + \frac{L'(Q)(L'(Q) - (n-1)\eta'(Q))}{(n-1)Q} \\ & = \frac{(n-1)^2\eta'(Q)^2 + 4L'(Q)^2 - 4L'(Q)(n-1)\eta'(Q)}{4(n-1)Q} \\ & = \frac{((n-1)\eta'(Q) - 2L'(Q))^2}{4(n-1)Q} > 0 \end{aligned}$$

So, if $(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q) \leq 0$, the surplus is maximized with full information, whatever the value of a .

Now, assume that $(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q) > 0$.

$F'(Q)L''(Q) + \frac{L'(Q)(L'(Q) - (n-1)\eta'(Q))}{(n-1)Q} = 0$ is equivalent to the following polynomial:

$$L'(Q)^2 - (n-1)\eta'(Q)L'(Q) + (n-1)QF'(Q)L''(Q) = 0$$

It is equivalent with respect to a to:

$$\begin{aligned} & (QF''(Q) + (n+1)F'(Q) + an)^2 - (n-1)\eta'(Q)(QF''(Q) + (n+1)F'(Q) + an) \\ & + (n-1)QF'(Q)L''(Q) = 0 \\ \Leftrightarrow & a^2n^2 + ((n+3)F'(Q) - (n-3)QF''(Q))an \\ & + (QF''(Q) + (n+1)F'(Q))(2F'(Q) - (n-2)QF''(Q)) + (n-1)QF'(Q)L''(Q) = 0 \end{aligned}$$

One can check that the solutions to this polynomial with respect to a are:

$$a_{1s} = -\frac{\sqrt{(n-1)}\sqrt{(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - \frac{F'(Q) - QF''(Q)}{2}$$

and

$$a_{2s} = \frac{\sqrt{(n-1)}\sqrt{(n-1)\eta'(Q)^2 - 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - \frac{F'(Q) - QF''(Q)}{2}$$

It is direct that this polynomial is convex since the only term of order 2 is $a^2n^2 > 0$. Thus the polynomial is negative between the roots and positive elsewhere. ■

Lemma 4. $\mathbb{E}(\Pi(Q)|\lambda)$ is increasing (resp. decreasing) in λ if the profit is convex in the belief μ_h , i.e. if $\frac{QF'(Q)}{L'(Q)}$ is an increasing (resp. decreasing) function. Then in the first case, the profit maximizer precision is $\lambda_P = 1$, and in the second case $\lambda_P = \frac{1}{2}$. As well, the profit is increasing (resp. decreasing) with information precision if:

$$\eta''(Q) < (>) \underbrace{\rho(Q) + \frac{L'(Q)}{Q}}_{>0} \equiv \bar{\rho}$$

Proof. Note $Q = Q^*(\mu_h)$.

$$\Pi(Q) = QF(Q) - \int_0^Q F(x)dx$$

Then, by differentiating the profit with respect to μ_h :

$$\begin{aligned} \frac{\partial \Pi(Q)}{\partial \mu_h} &= \frac{\partial Q}{\partial \mu_h} [QF(Q) + F(Q)] - \frac{\partial Q}{\partial \mu_h} F(Q) \\ \frac{\partial \Pi(Q)}{\partial \mu_h} &= \frac{\partial Q}{\partial \mu_h} QF(Q) \\ \frac{\partial \Pi(Q)}{\partial \mu_h} &= \frac{n\zeta QF'(Q)}{L'(Q)} \end{aligned}$$

Thus, the expected profit is increasing if $\frac{QF'(Q)}{L'(Q)}$ is increasing in Q . The decreasing profit case works as well.

To conclude:

$$\begin{aligned} &\left(\frac{QF'(Q)}{L'(Q)} \right)' > 0 \\ \Leftrightarrow &\frac{L'(Q)F'(Q)}{L'(Q)^2} + \frac{QL'(Q)F''(Q)}{L'(Q)^2} > \frac{QL''(Q)F'(Q)}{L'(Q)^2} \\ \Leftrightarrow &L'(Q)(F'(Q) + QF''(Q)) > QL''(Q)F'(Q) \\ \Leftrightarrow &Q\eta''(Q) + nQF''(Q) < \frac{L'(Q)(F'(Q) + QF''(Q))}{F'(Q)} \\ \Leftrightarrow &\eta''(Q) + nF''(Q) < \frac{L'(Q)}{Q} + \frac{(\eta'(Q) + an + nF'(Q))F''(Q)}{F'(Q)} \\ \Leftrightarrow &\eta''(Q) + nF''(Q) < \frac{L'(Q)}{Q} + \rho + nF''(Q) \\ \Leftrightarrow &\eta''(Q) < \rho(Q) + \underbrace{\frac{L'(Q)}{Q}}_{>0} \equiv \bar{\rho} \end{aligned}$$
■

Corollary 3. Note $a_P = \frac{QF'(Q)L''(Q)}{n\eta'(Q)} - \frac{\eta'(Q)}{n} - F'(Q)$. The profit is increasing (resp. decreasing) with information precision if:

$$\begin{cases} \text{In case where } \eta'(Q) < 0, \text{ if } a > (<)a_P \\ \text{In case where } \eta'(Q) < 0, \text{ if } a < (>)a_P \end{cases} \quad a_P$$

When the supply curve F is convex, increasing parameter a increases unambiguously the span (of η'') where the owners prefer information. Otherwise, increasing parameter a decreases the span (of η'') where the owners prefer information if $\eta'(Q) = QF''(Q) + F'(Q) < 0$.

Proof. By Lemma 4, the profit is increasing with information precision if:

$$\eta''(Q) < \rho(Q) + \underbrace{\frac{L'(Q)}{Q}}_{>0} \equiv \bar{\rho}$$

Re-writing the expression and assuming that $\eta'(Q) > 0$, we get:

$$\begin{aligned} an \frac{\eta'(Q)}{QF'(Q)} &> \eta''(Q) - \frac{F''(Q)\eta'(Q)}{F'(Q)} - \frac{\eta'(Q) + nF'(Q)}{Q} \\ \Leftrightarrow a &> \frac{QF'(Q)\eta''(Q)}{n\eta'(Q)} - \frac{QF''(Q)}{n} - \frac{F'(Q)(\eta'(Q) + nF'(Q))}{n\eta'(Q)} \\ \Leftrightarrow a &> \frac{QF'(Q)\eta''(Q)}{n\eta'(Q)} - \frac{\eta'(Q)}{n} - \frac{F'(Q)^2}{\eta'(Q)} \\ \Leftrightarrow a &> \frac{QF'(Q)L''(Q)}{n\eta'(Q)} - \frac{QF'(Q)nF''(Q)}{n\eta'(Q)} - \frac{\eta'(Q)}{n} - \frac{nF'(Q)^2}{n\eta'(Q)} \\ \Leftrightarrow a &> \frac{QF'(Q)L''(Q)}{n\eta'(Q)} - \frac{F'(Q)n(QF''(Q) + F'(Q))}{n\eta'(Q)} - \frac{\eta'(Q)}{n} \\ \Leftrightarrow a &> \frac{QF'(Q)L''(Q)}{n\eta'(Q)} - \frac{\eta'(Q)}{n} - F'(Q) \end{aligned}$$

We solve by analogy the case with $\eta'(Q) < 0$. ■

Proposition 3. Whenever $n \geq 1$, if $Q \left(1 + \frac{F'(Q)}{L'(Q)}\right)$ is increasing (resp. decreasing), then the welfare is increasing (resp. decreasing) with information precision. As well, the welfare is increasing (resp. decreasing) with information precision if:

$$\eta''(Q) < (>)\rho(Q) + \underbrace{\frac{L'(Q)(L'(Q) + F'(Q))}{QF'(Q)}}_{>0} \equiv \bar{\rho}$$

Proof. The economic welfare is the sum of the buyers' surplus and the owners' profit. Then, we can write:

$$W(Q) = \int_0^Q D^{-1}(x) - P(x)dx = \int_0^Q \mathbb{E}(Z|S) - ax - F(x)dx$$

Therefore, the expected economic welfare at equilibrium can be written (with $Q = Q^*(\mu_h)$):

$$W(Q) = Q \left(\mu_h \zeta + z_l - \frac{1}{2}aQ \right) - \int_0^Q F(q)dq$$

We can then deduce the derivative with respect to λ :

$$\frac{\partial W(Q)}{\partial \mu_h} = \frac{\partial Q}{\partial \mu_h} (\mu_h \zeta + z_l - aQ - F(Q)) + Q\zeta$$

From sFOC we know that $\mu_h \zeta + z_l - aQ - F(Q) = \frac{Q}{n} F'(Q)$. It follows:

$$\begin{aligned} \frac{\partial W(Q)}{\partial \mu_h} &= \frac{n\zeta}{L'(Q)} \frac{QF'(Q)}{n} + Q\zeta \\ &= \zeta \times Q \left(1 + \frac{F'(Q)}{L'(Q)} \right) \end{aligned}$$

Consequently, the economic welfare is increasing in the precision if $x \mapsto x \left(1 + \frac{F'(x)}{L'(x)} \right)$ is an increasing function.

To conclude:

$$\begin{aligned} &\left(Q \left(1 + \frac{F'(Q)}{L'(Q)} \right) \right)' > 0 \\ \Leftrightarrow &\frac{QL''(Q)F'(Q)}{L'(Q)^2} < \frac{L'(Q)^2 + L'(Q)F'(Q)}{L'(Q)^2} + \frac{QL'(Q)F''(Q)}{L'(Q)^2} \\ \Leftrightarrow &QL''(Q)F'(Q) < L'(Q)(L'(Q) + F'(Q) + QF''(Q)) \\ \Leftrightarrow &Q\eta''(Q) + nQF''(Q) < \frac{L'(Q)(L'(Q) + F'(Q) + QF''(Q))}{F'(Q)} \\ \Leftrightarrow &\eta''(Q) + nF''(Q) < \frac{L'(Q)(L'(Q) + F'(Q))}{Q} + \frac{(\eta'(Q) + an + nF'(Q))F''(Q)}{F'(Q)} \\ \Leftrightarrow &\eta''(Q) + nF''(Q) < \frac{L'(Q)(L'(Q) + F'(Q))}{Q} + \rho + nF''(Q) \\ \Leftrightarrow &\eta''(Q) < (>) \underbrace{\rho(Q) + \frac{L'(Q)(L'(Q) + F'(Q))}{QF'(Q)}}_{>0} \end{aligned}$$

■

Corollary 4. The welfare is increasing with information precision when:

$$(QF''(Q) + F'(Q))^2 + 4QF'(Q)(QF'''(Q) + (n+2)F''(Q)) = \eta'(Q)^2 + 4QF'(Q)L''(Q) \leq 0$$

Note

$$a_{1w} = -\frac{\sqrt{\eta'(Q)^2 + 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - F'(Q)$$

and

$$a_{2w} = \frac{\sqrt{\eta'(Q)^2 + 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - F'(Q)$$

And, the welfare is increasing (resp. decreasing) when $\eta'(Q)^2 + 4QF'(Q)L''(Q) > 0$ if:

$$\begin{cases} \text{in case where } a_{2w} < 0 \\ \text{in case where } a_{2w} > 0 \text{ and } a_{1w} < 0, \text{ if } a > (<)a_{2w} \\ \text{in case where } a_{1w} > 0, \text{ if } a > a_{2w} \text{ or } a < a_{1w}, (\text{ if } a_{1w} < a < a_{2w}) \end{cases}$$

When the supply curve F is convex, increasing parameter a increases unambiguously the span (of η'') where the welfare increases with information. Otherwise, increasing parameter a decreases the span (of η'') where the welfare increases with information if $\eta'(Q) = QF''(Q) + F'(Q) < 0$.

Proof. By the proof of Proposition 3, the welfare is increasing with information precision if:

$$\begin{aligned} QL''(Q)F'(Q) &< L'(Q)(L'(Q) + F'(Q) + QF''(Q)) \\ (\Leftrightarrow QL''(Q)F'(Q) - L'(Q)(L'(Q) + \eta'(Q)) &< 0) \end{aligned}$$

Assume $\eta'(Q)^2 + 4QF'(Q)L''(Q) \leq 0$. Then,

$$QL''(Q)F'(Q) \leq -\frac{\eta'(Q)^2}{4}$$

Thus,

$$\begin{aligned} QF'(Q)L''(Q) - L'(Q)(L'(Q) + \eta'(Q)) &< -\frac{\eta'(Q)^2}{4} - L'(Q)(L'(Q) + \eta'(Q)) \\ &= -\frac{\eta'(Q)^2}{4} - L'(Q)^2 - L'(Q)\eta'(Q) \\ &= -\frac{(\eta'(Q) - 2L'(Q))^2}{4} < 0 \end{aligned}$$

So, if $\eta'(Q)^2 + 4QF'(Q)L''(Q) \leq 0$, the welfare is maximized with full information, whatever the value of a .

Now, assume that $\eta'(Q)^2 + 4QF'(Q)L''(Q) > 0$.

$QL''(Q)F'(Q) - L'(Q)(L'(Q) + \eta'(Q)) = 0$ is equivalent to the following polynomial:

$$(QF''(Q) + (n+1)F'(Q) + an)^2 + \eta'(Q)(QF''(Q) + (n+1)F'(Q) + an) - QL''(Q)F'(Q) = 0$$

It is equivalent with respect to a to:

$$\begin{aligned} & a^2n^2 + ((2n+3)F'(Q) + 3QF''(Q))an \\ & + (QF''(Q) + (n+1)F'(Q))((n+2)F'(Q) + 2QF''(Q)) + QL''(Q)F'(Q) = 0 \end{aligned}$$

One can check that the solutions to this polynomial with respect to a are:

$$a_{1w} = -\frac{\sqrt{\eta'(Q)^2 + 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - F'(Q)$$

and

$$a_{2w} = \frac{\sqrt{\eta'(Q)^2 + 4QF'(Q)L''(Q)}}{2n} - \frac{3\eta'(Q)}{2n} - F'(Q)$$

It is direct that this polynomial is convex since the only term of order 2 is $a^2n^2 > 0$. Thus the polynomial is negative between the roots and positive elsewhere. ■

Lemma 5. When $\mu_0 = \frac{1}{2}$, whenever $n \geq 1$ and (1) $\frac{F'(Q)}{L'(Q)}$ increases, $\lambda_C = 1$. If (2) $\frac{F'(Q)}{L'(Q)}$ decreases, $\lambda_C = 1$ when (2i) $m(Q) > 0$ and $\lambda_C = \frac{1}{2}$ when (2ii) $m(Q) < 0$.

Proof. First note that if (1) $\frac{F'(Q)}{L'(Q)}$ increases, by Lemma 2, the *ex ante* mean price increases with respect to λ . Then, by Lemma 3, all owners prefer the maximal precision (strictly for the ones who sell their capacity unit).

Now, assume $\frac{F'(Q)}{L'(Q)}$ decreases. Owners that always produce prefers $\lambda_C = \frac{1}{2}$ since their profit increase with the expected price, which is maximal when $\lambda = \frac{1}{2}$.

Owners with bids included in $[F(Q(\mu_h = 0)), \hat{b}]$ prefers $\lambda_C = \frac{1}{2}$ as well. Recalling that for them: $F(Q^*(\mu_0)) - b_i > \mu_h(F(Q^*(1)) - b_i)$, one can find that for any $\tilde{\lambda} \in (\frac{1}{2}, 1]$, $\Pi(\tilde{\lambda}) < \Pi(\lambda = \frac{1}{2})$. Indeed, we know that: $\mathbb{E}(F(Q^*|\tilde{\lambda})) < F(Q^*|\lambda = \frac{1}{2})$, then $\mathbb{E}(F(Q^*|\tilde{\lambda})) - b < F(Q^*|\lambda = \frac{1}{2}) - b$. And the owner prefers to always produce since if he does not produce in the low signal case, he gets at most $\Pi(\lambda = 1)(= \frac{1}{2}[F(Q^*(\mu_h)(\lambda = 1)) - b])$ which is less than $\Pi(\lambda = \frac{1}{2})$ by hypothesis.

Thus, if $m(Q) < 0$, a majority prefers the lowest precision and $\lambda_c = \frac{1}{2}$.

To see why $m(Q) > 0$ implies that a majority prefers $\lambda_C = 1$, note that owners that produce only in the high signal case choose $\lambda_C = 1$ to maximize $F(Q_h^*(\lambda))$. Then, we just have to show that each owner with $b > \hat{b}$ wants to produce only with the high signal.

We recall that for them: $\mathbb{E}(F(Q^*(\lambda = \frac{1}{2})) - b(Q)) < \frac{1}{2}(F(Q_h^*(\lambda = 1)) - b(Q))$.

For owners whose the bid is included in $(\hat{b}, F(Q^*(\lambda = \frac{1}{2}))]$, if they want to produce both when s_h and s_l , they should prefer $\lambda_C = \frac{1}{2}$ to maximize their profit. However

$\Pi(\lambda = 1) > \Pi(\lambda = \frac{1}{2})$ for them, since $b > \hat{b}$. Finally they should only produce in high signal case.

For owners whose the bid is included in $(F(Q^*(\lambda = \frac{1}{2})), F(Q_h^*(\lambda = 1))]$, they prefer $\lambda_c = 1$, because they never sell their capacity when $\lambda = \frac{1}{2}$ while they do produce in the high signal case.

Finally, if $m(Q) > 0$, a majority prefers the highest precision and $\lambda_c = 1$. ■

Lemma 6. Total quantities at the high and low equilibria are increasing concave functions with respect to n .

Proof. By transforming sFOC, we get $\mathbb{E}(Z|s) - \left(\frac{\partial F(Q^*)}{\partial q} \frac{Q^*}{n} + F(Q^*) + a \times Q^* \right) = 0$. The implicit differentiation with respect to n gives:

$$\begin{aligned} \frac{\partial Q}{\partial n} &= \frac{\frac{F'(Q^*)Q^*}{n^2}}{\left(\frac{F''(Q^*)Q^*}{n} + \frac{F'(Q^*)}{n} + F'(Q^*) + a \right)} = \frac{F'(Q^*)Q^*}{n(F''(Q^*)Q^* + (n+1)F'(Q^*) + an)} > 0 \\ \frac{\partial^2 Q}{\partial n^2} &= -\frac{F'(Q^*)Q^*(F''(Q^*)Q^* + (2n+1)F'(Q^*) + 2an)}{n^2(F''(Q^*)Q^* + (n+1)F'(Q^*) + an)^2} < 0 \end{aligned}$$
■

Lemma 7. For any thrice differentiable supply curve, it exists $N \in \mathbb{N}$ such that $\forall n > N$: If (a) $F'' < 0$, then (a2i) $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0$ and $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$. If (b) $F'' > 0$, then (b2i) $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$ and $\frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$.

Proof. When buyers behave in a competitive way (i.e. $n \rightarrow \infty$), previous computations simplify since in equilibrium, the marginal value is equalized with the price. Essentially, $L'(Q^*)$ becomes $L'(Q^*) \equiv F'(Q) + a$, since we have the next competitive equilibrium condition:

$$\mathbb{E}(Z|s) - aQ^* = F(Q^*) \quad (\text{CEC})$$

Again, by implicit differentiation, we can write:

$$\frac{dQ^*}{d\mu_h} = \frac{\zeta}{L'(Q^*)} = \frac{\zeta}{F'(Q^*) + a} > 0 \Rightarrow \frac{\partial^2 Q^*}{\partial \mu_h^2} = -\frac{\zeta F''(Q^*)}{(F'(Q^*) + a)^2} \quad (\text{E.1})$$

The price's second derivative with respect to μ_h is:

$$\frac{\partial P^*(\mu_h)}{\partial \mu_h} = \frac{\partial F(Q^*(\mu_h))}{\partial Q^*(\mu_h)} \frac{\partial Q^*(\mu_h)}{\partial \mu_h} = F'(Q^*) \times \frac{\zeta}{F'(Q^*) + a} \Rightarrow \frac{\partial^2 P^*(\mu_h)}{\partial \mu_h^2} = \frac{a\zeta F''(Q)}{(F'(Q^*) + a)^2} \quad (\text{E.2})$$

The result is direct. ■

Proposition 5. If (a) $F'' > 0$, then $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0 \Rightarrow \frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$.

If (b) $F'' < 0$, then $\frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0 \Rightarrow \frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$.

Proof. First recall that L' and F' are both positive by hypothesis. We know that $L''(Q) < 0 \Leftrightarrow \frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$. As well, we know that $F''(Q)L'(Q) - F'(Q)L''(Q) > 0 \Leftrightarrow \frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$. It is directly seen that if (b), $L''(Q) > 0 \Leftrightarrow \frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} < 0$ implies that $F''(Q)L'(Q) - F'(Q)L''(Q) < 0 \Leftrightarrow \frac{\partial \mathbb{E}(P^*)}{\partial \lambda} < 0$. Similarly, if (a), $L''(Q) < 0 \Leftrightarrow \frac{\partial \mathbb{E}(Q^*)}{\partial \lambda} > 0$ implies that $F''(Q)L'(Q) - F'(Q)L''(Q) > 0 \Leftrightarrow \frac{\partial \mathbb{E}(P^*)}{\partial \lambda} > 0$. By contrapositive, we can deduce both statements. ■

Proposition 6. When n is large enough, preferences can be characterized with respect to the curvature of the bid function:

| F'' | | $-\frac{F'(F'+a)}{aQ}$ | 0 | $\frac{F'+a}{Q}$ | |
|------------------|---------------|---------------------------|---------------------------|------------------|---------------------------|
| Buyers' Surplus | | $\lambda_S = 1$ | $\lambda_S = 1$ | $\lambda_S = 1$ | $\lambda_S = \frac{1}{2}$ |
| Owners' Profit | | $\lambda_P = \frac{1}{2}$ | $\lambda_P = 1$ | $\lambda_P = 1$ | $\lambda_P = 1$ |
| Majority Winning | if $m(Q) > 0$ | $\lambda_C = 1$ | $\lambda_C = 1$ | $\lambda_C = 1$ | $\lambda_C = 1$ |
| | if $m(Q) < 0$ | $\lambda_C = \frac{1}{2}$ | $\lambda_C = \frac{1}{2}$ | $\lambda_C = 1$ | $\lambda_C = 1$ |
| Welfare | | $\lambda_W = 1$ | | | |

Table E.1: Maximizing precision under perfect competition

Proof. Combining Lemma 7 and Lemma 5, we deduce directly the statements on the Majority Winning precision.

For any total demanded quantity Q , the buyers' surplus is:

$$S(Q) = \int_0^Q D^{-1}(x) - P(Q)dx = \int_0^Q \mathbb{E}(Z|S) - ax - F(Q)dx$$

Therefore, the expected buyers' surplus at equilibrium can be written²:

$$\mathbb{E}(S(Q^*(\mu_h))) = Q^*(\mu_h) \left(\mu_h \zeta + z_l - \frac{1}{2}aQ^*(\mu_h) - F(Q^*(\mu_h)) \right)$$

Then, we can deduce the derivative with respect to μ_h in the competitive case:

$$\begin{aligned}
\frac{\partial \mathbb{E}(S(Q^*))}{\partial \mu_h} &= \frac{\partial Q^*}{\partial \mu_h} \underbrace{(\mu_h \zeta + z_l - aQ^* - F(Q^*) - F'(Q^*)Q^*)}_{=-Q^*F'(Q^*) \text{ by CEC}} + Q^* \zeta \\
&\Rightarrow \frac{\partial \mathbb{E}(S(Q^*))}{\partial \mu_h} = -\frac{\zeta Q^* F'(Q^*)}{F'(Q^*) + a} + Q^* \zeta = \frac{a\zeta Q^*}{F'(Q^*) + a} \\
&\Rightarrow \frac{\partial^2 \mathbb{E}(S(Q^*))}{\partial \mu_h^2} = \frac{\partial Q^*}{\partial \mu_h} \frac{a\zeta (F'(Q^*) + a) - a\zeta Q^* F''(Q^*)}{(F'(Q^*) + a)^2} \\
&\Rightarrow \frac{\partial^2 \mathbb{E}(S(Q^*))}{\partial \mu_h^2} = \frac{a\zeta^2}{(F'(Q^*) + a)^3} \times (F'(Q^*) + a - Q^* F''(Q^*))
\end{aligned} \tag{E.3}$$

²Cf. proof of Proposition 1.

The profit is expressed as follow (with Q is the aggregate quantities sold to the buyers):

$$\Pi(Q) = \int_0^Q F(Q) - F(x)dx$$

The derivative of the expected profit can be written³:

$$\begin{aligned} \frac{\partial \mathbb{E}(\Pi(Q^*))}{\partial \mu_h} &= \frac{d Q^*}{d \mu_h} \times Q^* F'(Q^*) = \frac{\zeta Q^* F'(Q^*)}{F'(Q^*) + a} \\ \Rightarrow \frac{\partial^2 \mathbb{E}(\Pi(Q^*))}{\partial \mu_h^2} &= \zeta \frac{d Q^*}{d \mu_h} \times \frac{(Q^* F''(Q^*) + F'(Q^*))(F'(Q^*) + a) - F''(Q^*) Q^* F'(Q^*)}{(F'(Q^*) + a)^2} \\ \Rightarrow \frac{\partial^2 \mathbb{E}(\Pi(Q^*))}{\partial \mu_h^2} &= \frac{\zeta^2}{(F'(Q^*) + a)^3} \times (a Q^* F''(Q^*) + a F'(Q^*) + F'(Q^*)^2) \end{aligned} \quad (\text{E.4})$$

Finally,

$$\begin{aligned} \frac{\partial^2 \mathbb{E}(W(Q^*))}{\partial \mu_h^2} &= \frac{\partial^2 \mathbb{E}(S(Q^*))}{\partial \mu_h^2} + \frac{\partial^2 \mathbb{E}(\Pi(Q^*))}{\partial \mu_h^2} \\ \Rightarrow \frac{\partial^2 \mathbb{E}(W(Q^*))}{\partial \mu_h^2} &= \frac{\zeta^2}{(F'(Q^*) + a)^3} \times (a F'(Q^*) + a^2 - a Q^* F''(Q^*)) + \\ &\quad \frac{\zeta^2}{(F'(Q^*) + a)^3} \times (a Q^* F''(Q^*) + a F'(Q^*) + F'(Q^*)^2) \\ \Rightarrow \frac{\partial^2 \mathbb{E}(W(Q^*))}{\partial \mu_h^2} &= \frac{\zeta^2}{(F'(Q^*) + a)} > 0 \end{aligned} \quad (\text{E.5})$$

The result is direct. ■

³Cf. proof of Lemma 4.

Appendix F

Majority-winning with a low probability of having a high state of the world

if $\mu_0 < \frac{1}{2}$, the probability to get a high signal decreases when the precision increases. It means that a part of the owners who prefer 1 to $\frac{1}{2}$ will prefer an other λ . As well for a part of the owners who prefer $\frac{1}{2}$ to 1. We show that there is a set of λ such that each λ maximizes the profit of an owner i . Note:

| Precision | Bid |
|--|--|
| $\lambda = \frac{1-\mu_0}{1-2\mu_0} - \frac{P^*(\mu_0) - \underline{b}^o}{(1-2\mu_0)^2(P^*(\mu_h) - \underline{b}^o)}$ | $\underline{b}^o = P^*(\mu_0) - \frac{(1-\mu_0)\mu_0 P^{*'}(\mu_h)}{1-2\mu_0}$ |
| $\bar{\lambda} = 1$ | $\bar{b}^o = P^*(1) - \frac{(1-\mu_0)P^{*'}(1)}{1-2\mu_0}$ |

Table F.1: Bounds on the interior precisions and their associated bids

Lemma 8. *If $\mu_0 < \frac{1}{2}$, a non negligible part of owners prefer a precision different from $\frac{1}{2}$ and 1. All the owners bidding in the interval $[\underline{b}^o, \bar{b}^o]$ prefer a different precision between $\underline{\lambda}$ and 1*

Proof. Considering the profit $\Pi_{S_h}(\lambda, b) = \mathbb{P}(s = S_h)(P^*(\mu_h) - b)$ of owners selling their capacity only when the high signal is displayed, the set of the interior precisions maximizing the profit of at least (in fact at most as well) one owner is the set of precisions such that the first order condition is null and such that the profit exceeds the profit with $\lambda = \frac{1}{2}$, i.e.:

$$\lambda^M \in]\frac{1}{2}, 1[\text{ such that } (i) \lambda^M \text{ maximizes } \Pi_{S_h}(\lambda, b)$$

$$\text{and such that } (ii) \mathbb{P}(s = S_h | \lambda^M)(P^*(\mu_h | \lambda^M) - b) \geq P^*(\mu_0) - b$$

For (i), we characterize the set of precisions such that the first order condition of $\Pi_{S_h}(\lambda, b)$ is null. For each bid b , one can find the precision λ^m that maximizes the profit (conditionally on selling only when the signal is high):

$$\begin{aligned} & \arg \max_{\lambda} \mathbb{P}(s = S_h)(P^*(\mu_h) - b) \\ \Leftrightarrow & \frac{\partial \mathbb{P}(s = S_h)}{\partial \lambda} \times (P^*(\mu_h) - b) + \mathbb{P}(s = S_h) \times P^{*'}(\mu_h) = 0 \\ \Leftrightarrow & \lambda^m = \frac{(1 - \mu_0)((1 - 2\mu_0)(P^*(\mu_h) - b) - \mu_0 P^{*'}(\mu_h))}{(1 - 2\mu_0)^2(P^*(\mu_h) - b)} \\ \Leftrightarrow & \lambda^m = \frac{1 - \mu_0}{1 - 2\mu_0} - \frac{(1 - \mu_0)\mu_0 P^{*'}(\mu_h)}{(1 - 2\mu_0)^2(P^*(\mu_h) - b)} \end{aligned}$$

For (ii), we need to define $b^o(\lambda)$ such that the owner who bids b^o is indifferent between $\lambda = \frac{1}{2}$ and a certain $\lambda \in (\frac{1}{2}, 1]$ that induces μ_h when the high signal is sent, i.e. (with $P^*(\mu_h)$ the price when the precision λ and the high signal S_h induce μ_h):

$$\mathbb{P}(s = S_h)(P^*(\mu_h) - b^o) = P^*(\mu_0) - b^o \Leftrightarrow b^o(1 - \mathbb{P}(s = S_h)) = P^*(\mu_0) - \mathbb{P}(s = S_h)P^*(\mu_h)$$

Note that $\forall b > b^o(\lambda)$, $\Pi_{S_h}(\lambda, b) > P^*(\mu_0) - b$, since:

$$\mathbb{P}(s = S_h)(P^*(\mu_h) - b) > P^*(\mu_0) - b \Leftrightarrow b > b^o(\lambda) = \frac{P^*(\mu_0) - \mathbb{P}(s = S_h)P^*(\mu_h)}{1 - \mathbb{P}(s = S_h)}$$

Thus, the set of λ^M is the set:

$$\begin{aligned} \lambda \in]\frac{1}{2}, 1[\text{ such that: } \exists i \text{ such that } \lambda = \lambda^m(b_i) \\ \text{and such that } b_i > b^o(\lambda^m) \end{aligned}$$

Now, we establish the bounds of the sets of λ^M and the associated bids b_i .

By implicit differentiation of the first order condition on λ^m , we find:

$$\frac{d\lambda^m}{db} = -\frac{(1 - 2\mu_0) \times \mathbb{P}(s = S_h)^3}{P^{*''}(\mu_h) \times \mu_0^2(1 - \mu_0)^2} > 0$$

We find by implicit differentiation of b^o :

$$\frac{db^o}{d\lambda} = -\frac{\frac{\partial \Pi}{\partial \lambda}}{1 - \mathbb{P}(s = S_h)} \text{ and } \frac{d^2 b^o}{d\lambda^2} = \frac{(1 - 2\mu_0)\frac{\partial \Pi}{\partial \lambda} - (1 - \mathbb{P}(s = S_h))\frac{\partial^2 \Pi}{\partial \lambda^2}}{(1 - \mathbb{P}(s = S_h))^2}$$

$\frac{db^o}{d\lambda}$ is negative if $\frac{\partial \Pi}{\partial \lambda}$ is positive and vice versa.

$\frac{\partial \Pi}{\partial \lambda}$ being decreasing everywhere, b^o is decreasing in λ for $\lambda < \underline{\lambda}$, with $\underline{\lambda}$ being the precision such that $\frac{db^o}{d\lambda} = 0$. Conversely, b^o is increasing in λ for $\lambda > \underline{\lambda}$, making $\underline{b^o} = b^o(\underline{\lambda})$ the minimal bid such that an owner is indifferent between $\frac{1}{2}$ and a certain $\lambda > \frac{1}{2}$. However,

this certain λ , that we noted $\underline{\lambda}$ is not the lowest precision such that an owner is indifferent between $\frac{1}{2}$ and the said precision. Nevertheless, as we will see below, it is the lowest precision (but $\frac{1}{2}$) that can be selected by an owner.

Since λ^m is increasing in b , there is an unique $\lambda^* = \underline{\lambda}$ that maximizes the profit of the owner who bids \underline{b}^o , and there is an unique bid \bar{b}^o such that $\lambda^* = 1$.

For \underline{b}^o , since \underline{b}^o is defined as $\frac{\partial \Pi}{\partial \lambda} = 0$, $\lambda^m = \lambda^o$. For \bar{b} , it is sufficient to replace λ^* by 1 in the first order condition.

Then, for each bid $\bar{b} > b > \underline{b}$, a different $\lambda^m(b) > \frac{1}{2}$ maximizes the profit of the owner who bids b . λ^m being strictly increasing, it means that between \underline{b}^o and \bar{b}^o , all owners choose a different λ .

| Precision | Bid |
|--|--|
| $\underline{\lambda} = \frac{1-\mu_0}{1-2\mu_0} - \frac{P^*(\mu_0) - \underline{b}^o}{(1-2\mu_0)^2(P^*(\mu_h) - \underline{b}^o)}$ | $\underline{b}^o = P^*(\mu_0) - \frac{(1-\mu_0)\mu_0 P^{*'}(\mu_h)}{1-2\mu_0}$ |
| $\bar{\lambda} = 1$ | $\bar{b}^o = P^*(1) - \frac{(1-\mu_0)P^{*'}(1)}{1-2\mu_0}$ |

Since $\underline{\mu}_h$ maximizes the profit for the bid \underline{b}^o , and since $\frac{d\lambda^*}{db} > 0$, for all the owners with $b > \underline{b}^o$, they prefer $\lambda^* > \underline{\lambda}$.

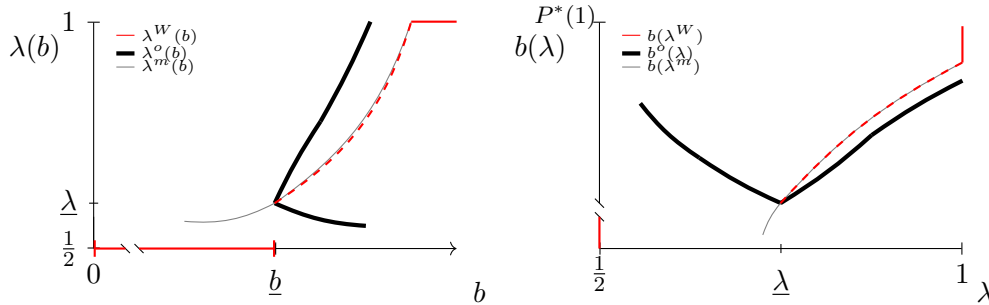


Figure F.1: Graphical example - Profit maximizing and indifference precisions (left-hand side), profit maximized and indifference bids (right-hand side)

On the left-hand side of figure F.1, we consider for each bid the precision that maximizes the profit (in red), and the precisions such that the owner is indifferent between $\frac{1}{2}$ and the said precisions (in black). Reciprocally, on the right-hand side, we draw the set of bids such that the owners maximize their profit with the given precision (in red) while the bids such that the owners are indifferent between $\frac{1}{2}$ and the said precision are in black. In both graphs, the grey line corresponds to the precisions that maximize the profit of the owner who sells only in the high signal case.

■

Few computations give:

$$\begin{aligned}\frac{\partial \hat{b}}{\partial \mu_0} &= (1 - \mu_0)P^{*'}(\mu_0) - (P^*(1) - P^*(\mu_0)) > 0 \text{ since } P^*(\mu_h) \text{ is concave,} \\ \frac{\partial \underline{b}}{\partial \mu_0} &= (1 - 2\mu_0)^2(P^{*'}(\mu_0) - P^{*'}(\mu_h)) + (1 - \mu_0)\mu_0(2P^{*'}(\mu_h) - (1 - 2\mu_0)(1 - \lambda)\lambda \frac{P^{*''}(\mu_h)}{\mathbb{P}(s=S_h)^2}) > 0, \\ \frac{\partial \bar{b}}{\partial \mu_0} &= -\frac{P^{*'}(1)}{(1 - 2\mu_0)^2} < 0\end{aligned}$$

Therefore, \hat{b} is increasing in μ_0 . Thus, if $\mu_0 > \frac{1}{2}$, there are more and more owners preferring $\frac{1}{2}$ as μ_0 increases –and less preferring 1.

If $\mu_0 < \frac{1}{2}$, there are also more owners preferring $\frac{1}{2}$ to 1 when μ_0 increases. As well, there are more owners preferring $\frac{1}{2}$ to any other precision when μ_0 increases because $P^*(\mu_0)$ increases. And, when μ_0 increases, more owners prefer 1 to the interior precisions, because the probability of receiving a high signal has increased. In other words, the preferences are more and more polarized, and both $\frac{1}{2}$ and 1 gain voters. At the limit $\mu_0 = \frac{1}{2}$, we have $\underline{b} = \hat{b} = \bar{b}$: $\frac{1}{2}$ and 1 are the only selected precisions.

If the owners are strategic in their choice, they all choose either $\frac{1}{2}$ or 1. Indeed, since $\lambda^m(b)$ is an increasing function, interior precisions can not be supported by more than one owners. Then, results remain unchanged:

Lemma 9. $\forall \mu_0$, whenever $n \geq 1$ and (1) $\frac{F'(Q)}{L'(Q)}$ increases, $\lambda_C = 1$. If (2) $\frac{F'(Q)}{L'(Q)}$ decreases and $\mu_0 \geq \frac{1}{2}$, $\lambda_C = 1$ when (2i) $m(Q) > 0$ and $\lambda_C = \frac{1}{2}$ when (2ii) $m(Q) < 0$.

Appendix G

Figures

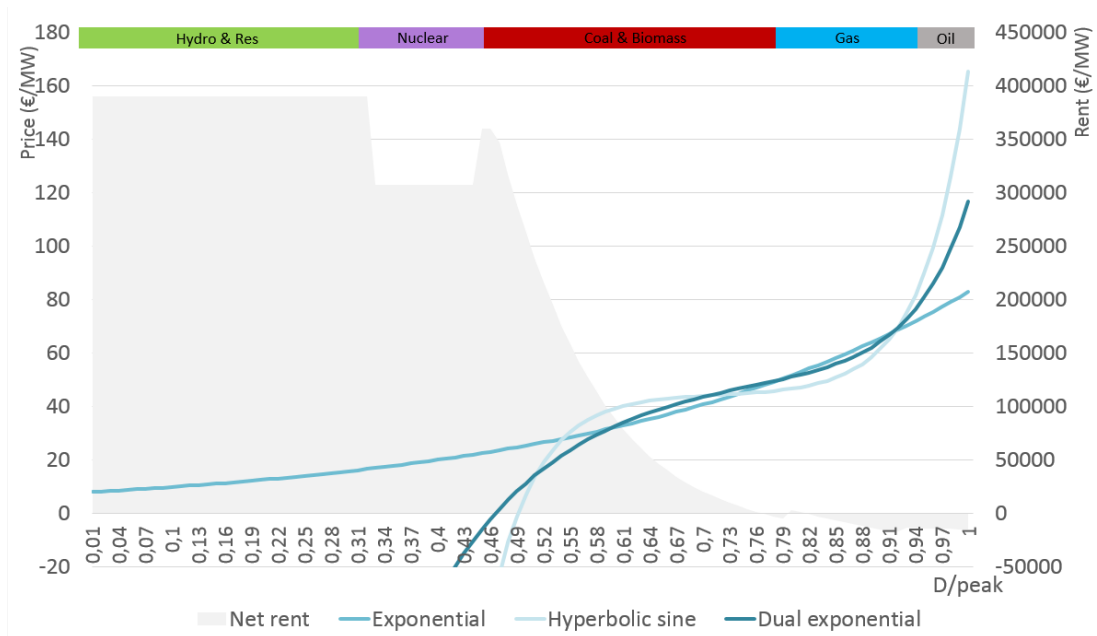


Figure G.1: Merit orders (He et al. [2013]) and net rent estimation (own calculations)

| Interval | Interval (MW) | α | β | γ | δ |
|------------|-----------------|-------------|---------|----------|------------------------|
| Quantile 1 | [72000; 80000] | -2717529,46 | 108,35 | -0,0014 | $6,39 * 10^{-9}$ |
| Quantile 2 | (80000; 95000] | 1895652,64 | -66,68 | 0,0008 | $-2,94 * 10^{-9}$ |
| Quantile 3 | [95000; 101000] | -3016576,63 | 89,09 | -0,0008 | $2,86E - 09 * 10^{-9}$ |

Table G.1: Coefficients of the Spline fit for the supply curve of Germany in 2010

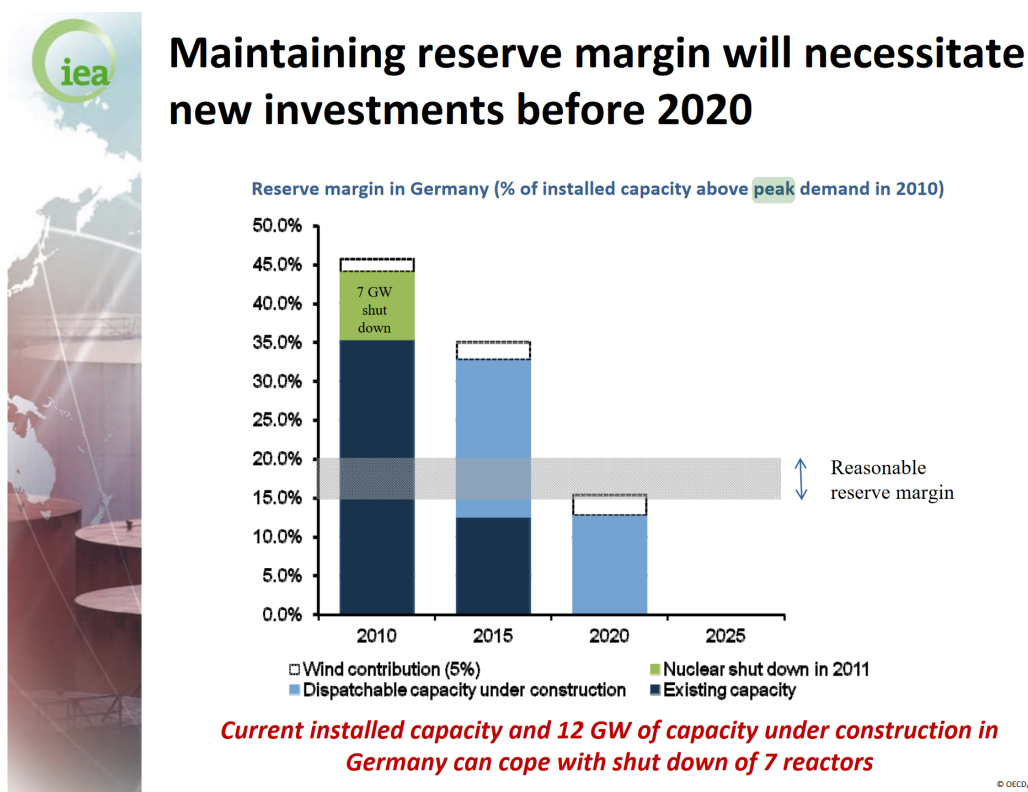


Figure G.2: Expected reserve margin evolution from IEA International Energy Agency [2010]

Forecast total obligation for France under different demand variants (in GW)

| Demand variant | 2016 | 2017 | 2018 | 2019 | 2020 |
|-----------------|-------|-------|-------|--------|--------|
| High | 90.4 | 91.2 | 92.0 | 92.6 | 93.4 |
| Baseline | 89.7 | 90.0 | 90.3 | 90.6 | 90.8 |
| Stronger DSM | 89.2 | 89.4 | 89.5 | 89.6 | 89.9 |
| Low | 88.8 | 88.6 | 88.4 | 88.3 | 88.0 |
| Security factor | 0.93* | 0.93* | 0.93* | 0.93** | 0.93** |

* Security factor validated for the first two years of the mechanism in the order of 22 January 2015

** Security factor assumed to be the same for the following two years

Figure G.3: Forecast total obligation for France under different demand variants (in GW) RTE [2015]

Appendix H

Structural under procurement

| $z_h = z_l$ | | $Q_1^t = 79.9 \text{ GW}$ | $Q_2^t = 87.1 \text{ GW}$ | $Q_3^t = 100.1 \text{ GW}$ | $Q_4^t = 104.5 \text{ GW}$ |
|--------------|-------------|---------------------------|---------------------------|----------------------------|----------------------------|
| $n = \infty$ | $\forall a$ | - | - | - | - |
| $n = 65$ | $a = 50$ | -12 | -26 | -2 | -3 |
| | $a = 20$ | -29 | -62 | -6 | -8 |
| | $a = 10$ | -55 | -119 | -12 | -17 |
| | $a = 5$ | -104 | -218 | -24 | -33 |
| $n = 4$ | $a = 50$ | -178 | -414 | -40 | -53 |
| | $a = 20$ | -401 | -988 | -102 | -128 |
| | $a = 10$ | -694 | -1 819 | -213 | -244 |
| | $a = 5$ | -1 112 | -3 081 | -467 | -444 |

Table H.1: Differentials in capacity procurement (MW)

In terms of procurement (table H.1), under procurements structurally increase as the level of competition (n) decreases. However, the size of market power is limited by the slope of the demand curve (implicit penalty). Indeed, it works as a retracting force since deviations from the competitive equilibrium are increasingly costly as a increases. Now, the slope of the supply curve also matters in terms of market power expression: the steeper it is, the more expensive it is to buy additional capacity. For instance, the Q_2^t case is characterized both by a greater F' and a much greater level of under procurement than the three other cases. Interestingly, we can observe that the effect of a on under procurement is not linear, and is modified with respect to the considered target. This effect obviously depends on the supply curve. When F' , is low (as in the third and fourth cases), the second derivative has a role to play. Indeed, when F'' is negative (as in the third case), the market power is decreasing in quantities: as a decreases, less and less quantities are procured. Under procurement is not only a way to decrease prices, but it also allows for more market power expression. On the contrary, F'' is positive at Q_4^t meaning that the marginal effect of reducing procurement on prices is decreasing. This somehow bounds the expression of market power and explains why under procurement is

relatively more important in the Q_3^t case than with Q_4^t (for $a = 5$) although the slope of the supply curve is locally more gentle.

Taking the most extreme case of under procurement, Q_2^t with a low slope, the effect of competition on procured quantities is represented graphically. The market power induced by 65 capacity homogeneous buyers with respect to perfect competition reduces procurement by 0.25% from 87100 MW to 86882 MW. If only 4 LSEs compete in the market, the capacity bought is further decreased to 84019 MW: the expression of market power allows capacity buyers to reduce their actual demand by 3.54% compared to the competitive state. As illustrated by figure H.1, market power is not linearly decreasing in n . The purple curves represent L : as F' increases, the difference between the light curve ($n = 4$) and the dark curve ($n = \infty$) increases which means that the first one will equal $\mathbb{E}(Z)$ (first order condition) sooner than the other. It is also noticeable from the figure that high competition ($n = 65$) results in an almost linear L contrary to the low competition case ($n = 4$). This is only natural since the smaller the oligopsony, the more self conscious they are of the steepness of the supply curve. A steep supply curve means that additional capacity is increasingly costly, and the less numerous they are, the greater their impact on price. Consequently, they benefit more from their own decision of buying less. All in all, L in the low competition case and the medium one tend to diverge when the supply curve changes shape. It is coherent with what we found in the previous section: when the supply curve shape is modified, the relative increases of both the markdown derivative and the supply curve derivative are modified in different ways. When the markdown has a large weight in sFOC, it may affect the preferences for precision.

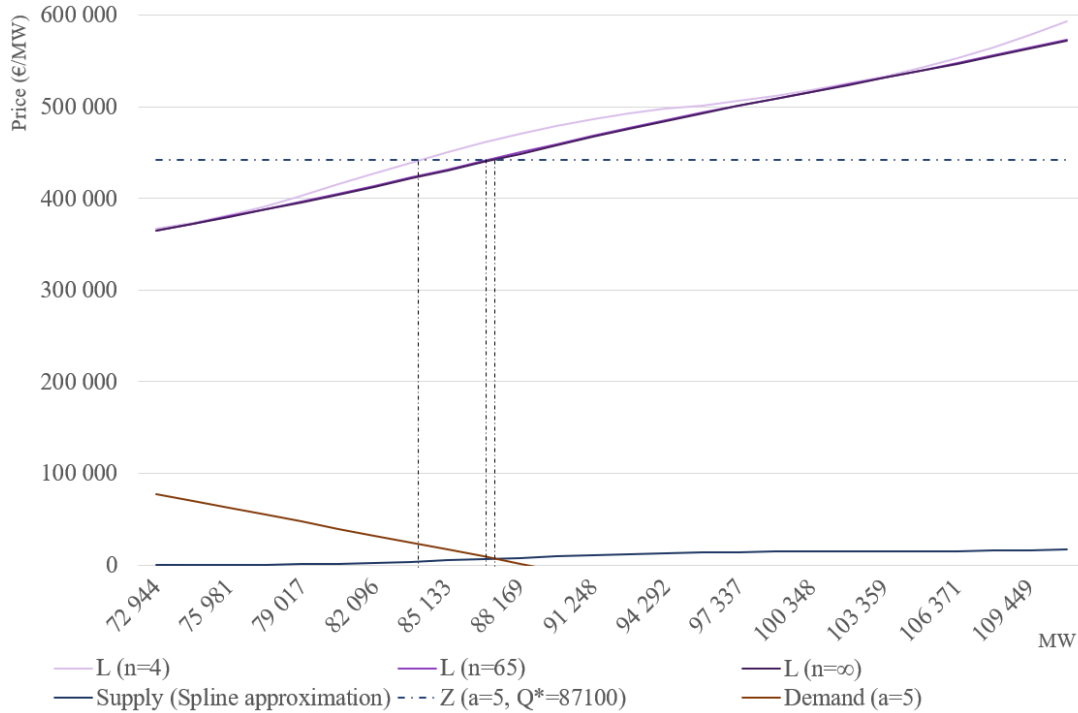


Figure H.1: Effect of competition on procured quantities for $a = 5$, $Z \approx 442382, 41$

Appendix I

Sensitivity on uncertainty

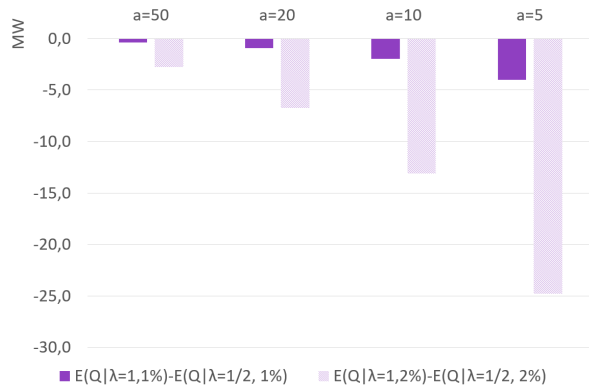


Figure I.1: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_1^t = 79900$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

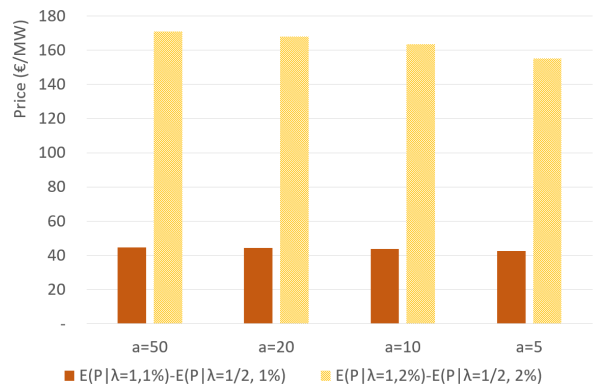


Figure I.2: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_1^t = 79900$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

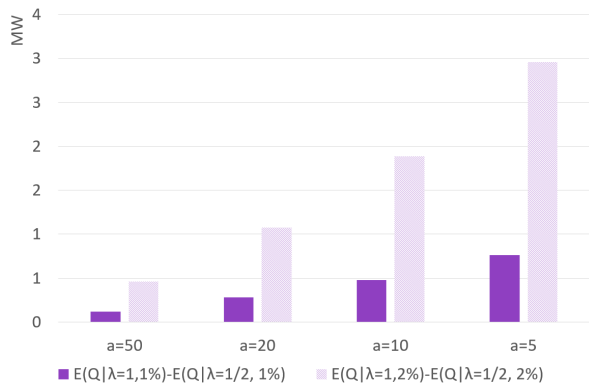


Figure I.3: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_2^t = 87100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

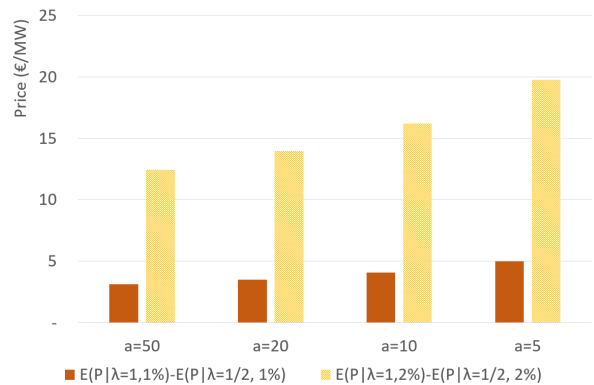


Figure I.4: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_2^t = 87100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

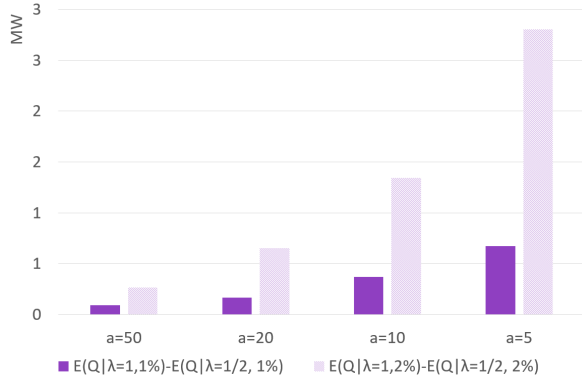


Figure I.5: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_3^t = 100100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

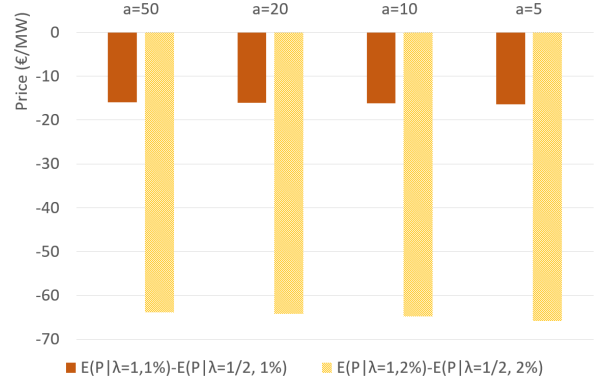


Figure I.6: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_3^t = 100100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

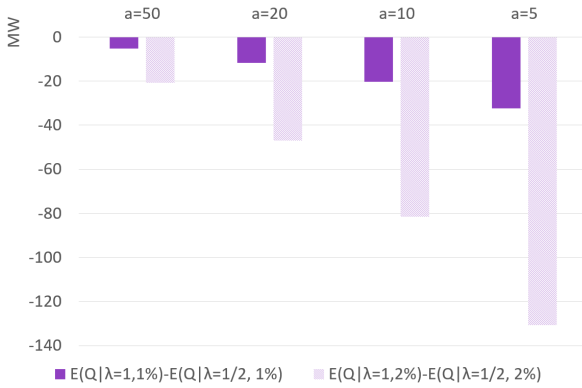


Figure I.7: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_4^t = 104500$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

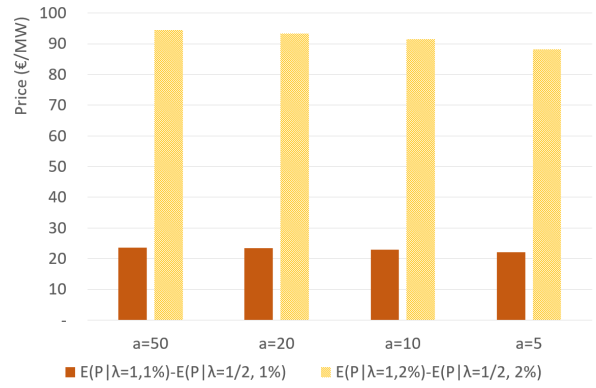


Figure I.8: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_4^t = 104500$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 65$)

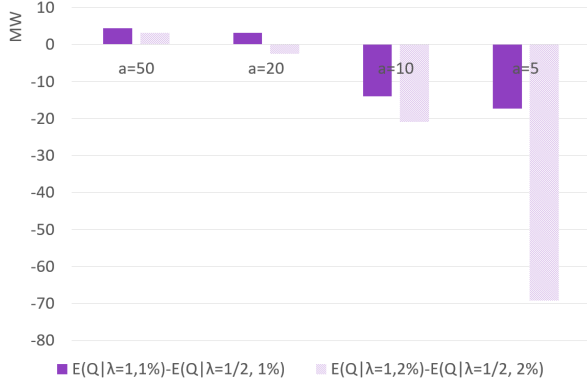


Figure I.9: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_1^t = 79900$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

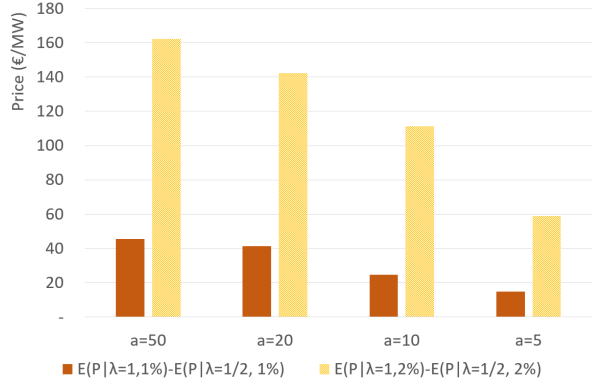


Figure I.10: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_1^t = 79900$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

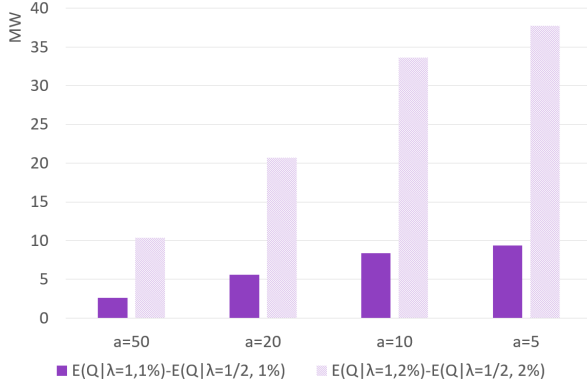


Figure I.11: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_2^t = 87100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

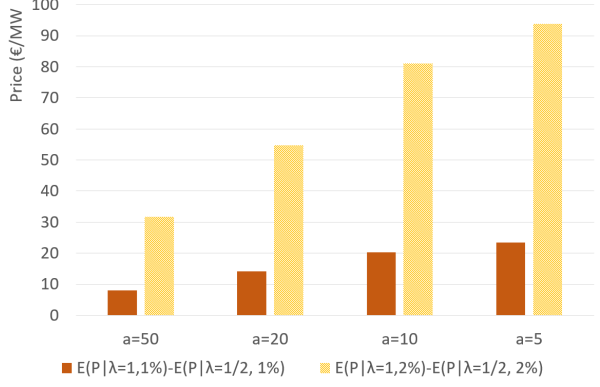


Figure I.12: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_2^t = 87100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

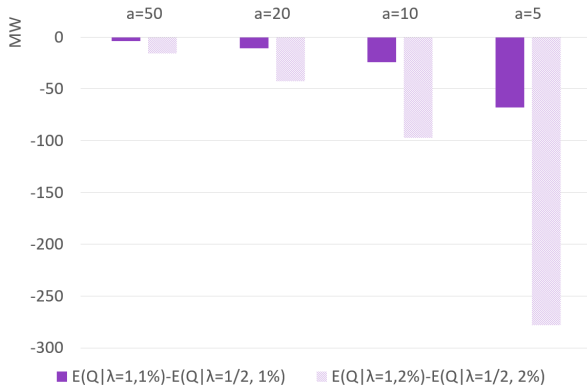


Figure I.13: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_3^t = 100100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

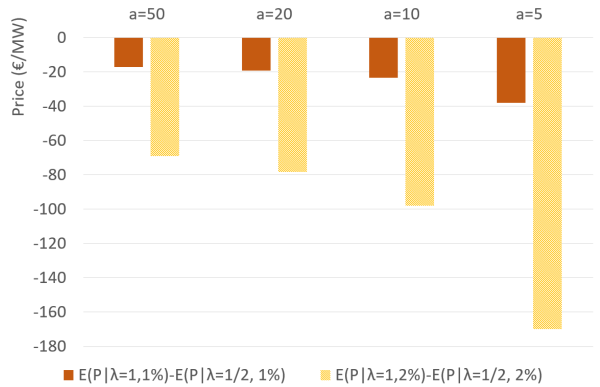


Figure I.14: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_3^t = 100100$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

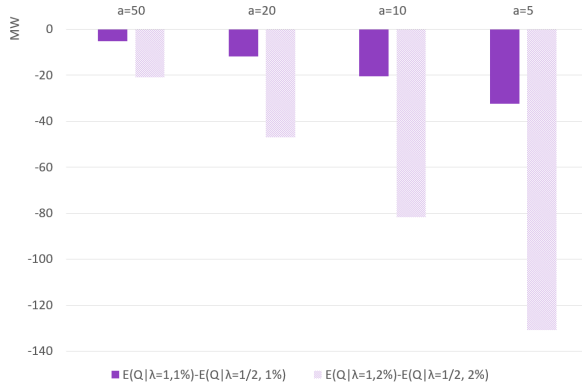


Figure I.15: Difference in mean quantities between the information ($\lambda = 1$) equilibrium ($Q_4^t = 104500$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

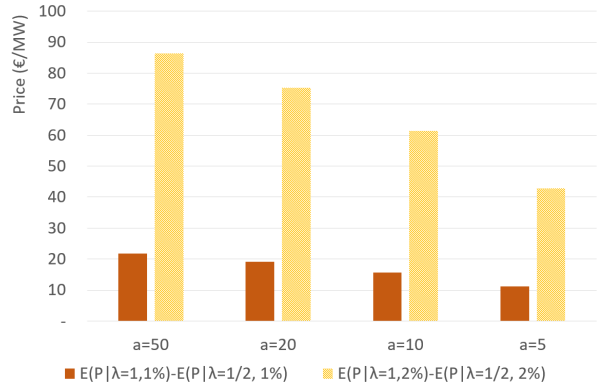


Figure I.16: Difference in mean prices between the information ($\lambda = 1$) equilibrium ($Q_4^t = 104500$ MW) and the no information ($\lambda = \frac{1}{2}$) equilibrium at ($n = 4$)

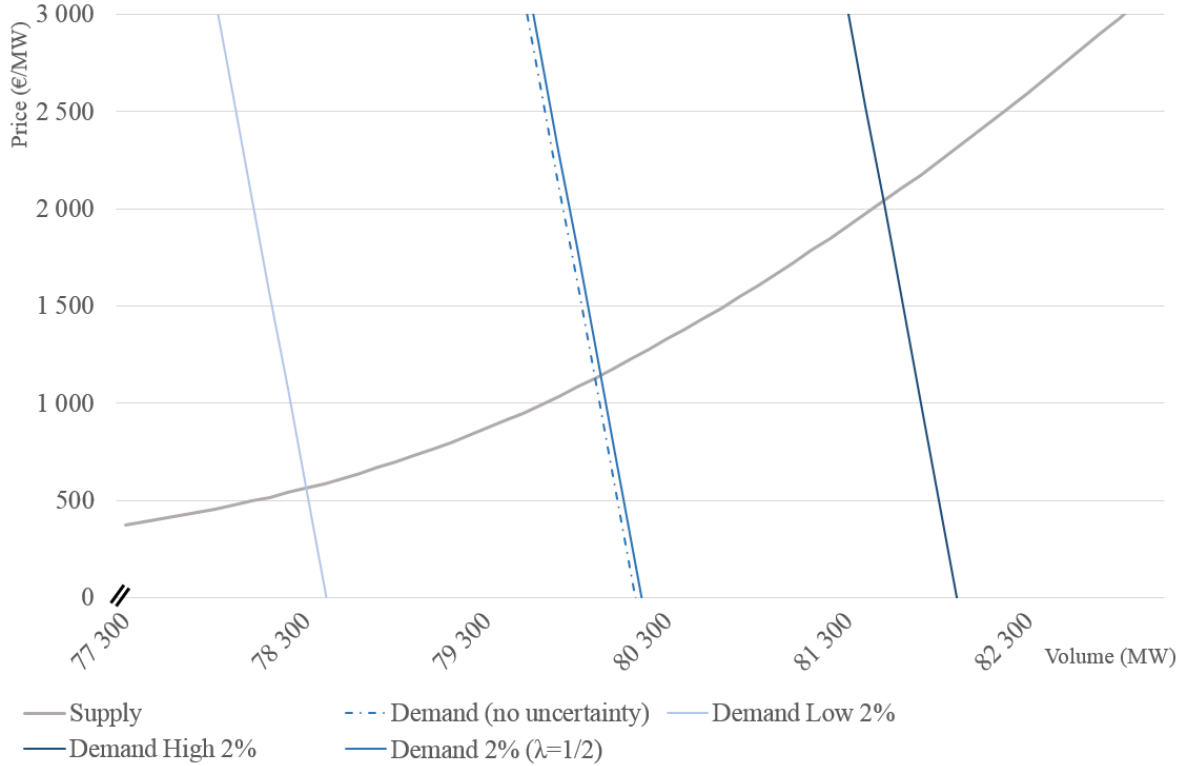


Figure I.17: Representation of the Q_1 case with both no uncertainty and 2% uncertainty with and without information ($a = 5$)

Appendix J

Demand-side design in capacity markets

J.1 Design related Information Precision in Capacity Markets

In a framework where the SoS depends on the ability of LSEs to collectively cover the aggregated peak demand to avoid rationing: the uncertainty is endemic and the forecast error can be costly. This is one of the difficulties in designing capacity markets: what is the fair risk that retailers/consumers should bear with respect forecasting and securing their future demand? With price insensitive end consumers - for technical reasons -, it is a complex trade off. As forward periods of 3 to 4 years are increasingly implemented, the risks related to forecast errors need to be tackled through the capacity market design itself. In addition to the well discussed degree of centralization, two approaches are observed in existing CRMs: (a) *ex ante* requirements hedge market actors against the forecast error while (b) the *ex post* requirements makes them accountable for it (see Table 3.1). As a consequence, the official peak demand forecast is unevenly informative depending on the capacity market design.

Indeed, in a mechanism that defines the capacity requirements *ex ante* like in Great Britain, any forecast error would only affect the end-users through the cost of capacity (over procurement) or eventual black-outs (under procurements). In case of discontentment, they might turn against the central authority, but the actual electricity market actors are not accountable for reliability: capacity owners receive what they deserve and LSEs pay what they are told to. This solution is broadly implemented in the US as well. The amount of capacity to be procured is fully known *ex ante* either for each LSE (former MISO) or for the whole system (ISO-NE, PJM) which is the central planner case¹. Full regulation equates perfect information: the forecast requirement of the central authority is fully instructive for them and this is true irrespective of actual scarcity in the market

¹Capacity market reality can also lie in between with a mix of bilateral trade, two sided auctions and/or one sided auction with an administrative demand curve (NYISO).

at a given delivery year.

On the contrary, the French mechanism makes the LSEs directly accountable for their reliability. They have to forecast their own requirements (based on peak demand) and procure its capacity equivalent. Regulatory parameters are set to hedge against temperature related forecast errors and normalize requirements to the SoS objective, but the actual requirements still depend on realized demand. This naturally shifts part of the cost of forecast error towards the LSEs: they have to procure capacity under uncertainty on the future realization of demand levels. The central authority's forecast gives a clue on the expected aggregated level of capacity, but this information is only partially instructive because of the myopic nature of the central authority. Because forecast errors decrease with aggregation, the central authority's forecast is likely to be more accurate than the LSE's one all things equal [Chen, 2017], but it remains imprecise. Accounting for the informational value of the forecast published as well as the uncertainty around their own realization, the LSEs procure the capacity they expect to need².

All in all, three main points make the French mechanism different from the most contemporary CRMs such as the British capacity market: (i) the procurement is decentralized and (ii) the risk related to demand unpredictability is left to the capacity buyers. The first point creates Cournot competition between LSEs because each of them receives the obligation to procure its share of capacity. The second point introduces uncertainty on the future level of capacity demand. Indeed, where the forecast is binding in Great Britain, it is rather the demand realization that is in France. In other words, *ex ante* requirement definition makes the aggregated requirement forecast fully informative to the market participants in Great Britain. It will only be partly informative in the French design because actual requirements (*ex post*) are based on peak demand realization rather than a forecast. Thus, the cost allocation of the mechanism (based on current or future peak share or even peak realization) does affect the uncertainty faced by the LSEs.

J.2 Designs of capacity markets: The British capacity market

The British capacity market was implemented as part of the Electricity Market Reform (EMR) which deals with sustainability, reliability and affordability in the system. The former seeks to comply with the 20-20-20 from the climate and energy package of the European commission³ while the second one seeks to meet a reliability standard of 3 hours of expected loss of load per capacity year⁴. The latter states that price inflation should be limited to ensure an access as universal as possible. In the Electricity Market Reform (EMR), the two first targets are set by the public authority and procured separately under the assumption that their public good attribute prevents efficient market

²See chapter J for more details.

³20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables, 20% improvement in energy efficiency.

⁴Loss of Load is defined, in the UK, as the time during which an instruction of brown out is issued or emergency options are activated in order to prevent a brown out.

outcomes. These two targets have been thought as complements in order to also achieve the affordability goal. Otherwise subsidized capacity, as tendered renewables, cannot be eligible for capacity payments. Yet, its inner reliability at peak is considered as secured by the central authority. However, this only represents a small share of the capacity required to cover the peak demand with a loss of load probability (LOLP) lower than 3 hours per year. The rest still needs to be procured through the capacity market. National Grid, the system operator, is mandated by the ministry on behalf of the end consumers to secure the capacity required to meet the reliability target four years in advance. In order to avoid the emergence of pivotal buyer, a slope is built through the definition of a "minimum" capacity where the price cap is reached and a "maximum" one where the price reaches zero. The resulting demand curve is built as follow:

- The capacity target: 46.3 GW for DY 2022-2023
- The net Cost Of New Entry (CONE)⁵ as estimated by the ministry: £49/kW/year for DY 2022-2023
- The price cap at 1.5 Net CONE at: £75/kW/year for DY 2022-2023
- The minimum and maximum capacity at: ± 1.5 GW

On the supply-side, a price taker threshold is defined at 0.5 Net CONE to force price competition between the existing capacity. The existing capacity cannot exit the auction⁶ before the price drops under £25/kW/year. From those characteristics, it results not only a steep demand curve, but also numerous low bids. The choice of the parameters reveals several elements that are key to understanding capacity markets. Firstly, the capacity target is not firm. What is called "target tolerances" reflects the myopic view of the public authority. Indeed, there is no technical way for the end consumer to express its precise preferences in terms of SoS, and when it comes to set a target several years ahead of peak demand realization, the level of procurement can only be an educated guess. For the defenders of capacity markets, its outcomes in terms of SoS are considered more desirable than the energy-only market outcomes. This is because the cost of a black-out is often higher than the cost of additional SoS. From the end consumers' perspective, whatever the reliability target set and reached, the captive consumers still pay for their capacity requirements: a "CM operational levy" and a "CM obligation levy" are charged to LSEs in proportion of their market share at peak⁷. End consumers also still face the cost of any black-out that would come to happen. In this framework, obtaining the least cost solution remains a recurrent discussion among public authorities.

⁵Cost of a new entrant (CCGT in 2014 and 2015 auctions) after accounting for wholesale and ancillary market revenues.

⁶Descending clock auction.

⁷4pm to 7pm, Monday to Friday during November to February.

J.3 Designs of capacity markets: The French capacity market

Hoping to minimize the deviation of the procurement from actual needs, France chose a decentralized design where the realized peak demand is binding instead of the forecasted peak demand. This design echoes the central authority's myopia with respect to future demand.

As in the UK, the reliability target is centrally defined by the public authority to cope with the non excludability of SoS. However, instead of procuring the capacity itself, the mandate is given to the LSEs that are then in charge of both the electricity and the SoS provided to the end consumers. Three years in advance, LSEs and network operators have to cover their future peak demand either through the auctions organized by EPEX Spot, or over-the-counter. When the delivery year is over, and peak demand have been quantified, the settlement process requires the agents either to adjust their positions, or to pay a non compliance penalty if they remain short. This is a two-edged sword since LSEs have a finer knowledge of their own demand and might even be able to reduce their peak demand if they have to pay for it. Nevertheless, demand forecasts are known to be more accurate when markets are centralized Chen [2017]. Indeed, demand tends to average out with the size of the market. That being said, the reliability target is translated into regulation through requirement parameters very different from those of the British design. The two following are published 4 years ahead, but individual targets remain uncertain:

- Thermo sensitivity coefficients: the weather normalization forces the LSEs to procure capacity as if extreme temperatures were reached (between -1.6°C and -4°C depending on the time of the day).
- The security factor scales the weather normalized peak with capacity needs: 0.93.

The weather correction aims both at SoS objectives since demand is highly correlated with temperatures, but also at hedging LSEs against the effect of weather uncertainty on peak demand. As a matter of fact, the LSEs are free to build their expectations individually based on predefined scaling parameter for their future peak demand:

$$\text{Obligation} = \text{security coefficient}(\text{realized consumption} + \text{weather correction})$$

On the supply-side, capacity is normalized into certificates with compulsory offer on the market. Bids are only constrained by a price cap and the regulator closely monitors the main integrated actors' trades. A capacity register is hold by RTE to keep track of every transaction. Quantities and prices are publicly available for transparency reasons, but not the identity of the agents involved.

Chapter 4

Capacity Remuneration in Power Markets: An Empirical Assessment of the Cost and Benefits of Precaution

Abstract

CRMs affect the total cost of electricity provision in different ways. While average wholesale electricity prices and investment costs are likely to be reduced, capacity needs to be paid for as an additional item. Whether the downward effects on system costs outweigh the cost of CRMs has so far remained largely unassessed in the academic literature. Total costs as indicated by the final prices paid by end-user prices will vary depending on the relative size of those contrasting effects. This chapter presents an econometric study of this overall –conditional– effect on final prices for end-users, thus providing insights on the net costs of providing higher reserve margins. Investigating the net cost of market designs with CRMs with a cross-country panel analysis yields limited evidence of a partial effect of CRM on industrial end-user prices. In some cases, the conditional average effect is even slightly negative, for instance in US markets. Overall, the implementation of a CRM is correlated with a reduction of the gap between industrial and residential end-user prices.

4.1 Introduction

In modern societies, access to electricity is the core of lifestyle, which results in power cuts being very harmful at every level. Of course, backup generators do exist and are often used where blackouts are the most costly, like in hospitals. But ordinary firms, administrations, individuals and agents, in general, are vulnerable to shortages: no computer or machinery means no work done for firms, a non-functioning traffic light could create accidents and frozen food gets lost when the power is off. The list of losses within the economy could be continued for long and no regulator can fully ignore it. With non-economically storable

electricity and inelastic demand, the ability to ensure continued power supply largely depends on installed (available) capacity.

As discussed in the general introduction, variations in the scarcity rent drive exit and entry in the energy-only market (EOM). However, those flows are unlikely to be optimal under real-life conditions. Indeed, electricity markets are empirically flawed with several suspected market imperfections¹ that might generate inefficiencies. If perfectly efficient markets are rarely considered as achievable by economists and practitioners, the particularities of electricity as a good generate concern about the cost of sub-optimal market outcomes in terms of reliability. The obstacles to optimal investment discussed in the literature [Stoft, 2002; Cramton and Ockenfels, 2012; Keppler, 2017] can be gathered into seven main categories: (i) captive consumers, (ii) market interventions, (iii) missing markets for services, (iv) missing money, (v) risk aversion and lack of hedging, (vi) asymmetric incentives and strategic behavior, (vii) externality attributes of security of supply (SoS)².

Capacity remuneration mechanisms (CRMs)³ address those potential imperfections in several ways. Mainly, CRMs increase SoS either by setting a fixed target on capacity and/or increasing the expected revenues. When electricity market revenues are supplemented by a specific capacity revenue, this is if the scarcity rent is partially or completely suppressed to the benefit of a fixed payment, CRMs act as a hedging instrument for the generators. This observation is subject to the fact that capacity is contracted on a longer basis than electricity. Mechanically, a reduction of the scarcity rent will, all other things equal, lead to lower price volatility and subsequent lower wholesale prices [Bajo-Buenestado, 2017]. Market risk is also reduced, affecting investment costs downward.

Numerical models tend to validate these effects under different settings. Indeed, chapter 2 has shown that CRMs effectively correct the market imperfections targeted. For instance, de Vries and Heijnen [2008] tests the efficiency of the EOM, capacity payment and obligations under demand uncertainty. They find all alternative market designs to perform better than the EOM and the capacity obligation to be more efficient both in terms of price levels (energy and capacity) and shortages. More specifically considering risk aversion, Petit et al. [2017]; de Vries and Heijnen [2008]; de Maere d'Aertrycke et al. [2017] illustrate how specific real-life conditions might affect market outcomes compared to the benchmark. Using a system dynamics model in perfect competition, Petit et al. [2017] find the loss of load⁴ (hours per year) to be higher and installed capacity to be

¹Since the causality between the identified market imperfections and the deviations from optimality has not been unambiguously determined, I refrain from using the term "market failure". Similarly, market imperfections are described as "suspected" or "potential" to reflect this missing link between the causes and the suspected effect.

²In this chapter, as in the others, security of supply and reliability are used indifferently although the former is formally a broader concept.

³This chapter will refer to CRMs mainly excluding the strategic reserve due to the differences in the levies at stake compared to the other types of common CRMs. This decision will be further discussed in subsequent sections.

⁴Loss of load: demand not satisfied.

lower under CRM than under scarcity pricing. However, extending their results to include risk aversion, they show that the loss of load grows with the risk aversion of the agents under scarcity pricing. On the contrary, risk aversion has very little impact on the loss of load under CRM. de Maere d’Aertrycke et al. [2017] shows that market incompleteness alone already generates inefficiencies, risk aversion further worsening the situation.

If chapter 2 shows that CRMs effectively reduce price volatility and investment cycles while increasing SoS, the modeling literature fails to unanimously conclude on the net cost for end consumers. In a context where welfare implications of choosing a CRM rather than an EOM design is largely unknown due to difficult quantification, such a decision can be seen as a precaution. In the remainder of this chapter, we will consider CRMs to be implemented as precautionary measures rather than a perfectly informed decision from the public authority. Such market intervention can be considered as exogenous to market conditions because it is based on the hypothesis that the costs of insufficient reliability will always be higher than the benefits brought by CRMs, rather than a known fact. This is supported by empirical observations since rare are the systems that have swung from one to the other⁵

This paves the way for the purpose of this chapter which is an attempt to empirically assess the net cost of precaution. Indeed, implementing a CRMs affect market outcomes in opposite directions compared to the benchmark. Mainly, electricity prices and investment costs are reduced while capacity is paid for through an additional cost component. Whether the downward effects on system costs outweigh the cost of the mechanism remain largely unassessed [Bublitz et al., 2019]. As a corollary, end-user prices will vary depending on the relative size of those contradictory effects on system costs. In this sense, the net effect of CRMs on end-users’ bill is difficult to estimate, let alone the welfare consequences. In other words, the research question is to understand if CRMs can secure a higher reserve margin –as suggested in chapter 2– without being disproportionately costly.

Existing CRMs spread the charge on per peak demand participation (MW) or per energy consumed (MWh). Following such a structural change in the market organization, end-users consequently face the three contradictory effects: the lower average wholesale electricity prices [Bajo-Buenestado, 2017] might be partially or totally compensated by the new capacity price component [de Vries, 2004; Iychettira et al., 2014; Cepeda and Finon, 2011]. The end-users face the net effect of CRMs implementation through a variation in their electricity bill that accounts for the three pre-cited effects. However, different categories of end consumers could be differently affected by such contradictory forces and redistribution effects become central. A good illustration is the newly implemented French capacity market. Being decentralized, it is the retailer’s decision to pass through the cost of capacity. On the capacity market, all residential consumers are profiled, meaning that whatever their consumption at scarcity, they all pay for the same amount of capacity. On the contrary, industrial end-user can get a finer estimation of their actual consumption

⁵The UK is a notable exception.

profile and personalize their contribution to the capacity charge. In general, industrial consumers benefit from greater bargaining power than residential ones as it is an increasing function of quantities and predictability. For the agent (load-serving entity) in charge, it generally results in a trade-off on how to charge capacity.

Powerful vectors of information, end-user prices embed all electricity cost components, which makes it the perfect playfield to catch the overall cost-efficiency of CRMs. Records of end-user electricity prices and CRM implementation both date back to the beginning of the 90s, providing the opportunity to empirically attempt measuring the (conditional) net effect of CRM implementation. Standing in the continuity of cross-country liberalization's assessments as performed by Steiner [2001]; Nagayama [2009]; Swadley and Yücel [2011]; Joskow [2006], this paper seeks to set out a relationship between CRM implementation and price levels to get a first peek at the net cost compared to alternative market designs (mainly previous ones). This is done disregarding the efficiency in terms of security of supply⁶. Taking advantage of the panel approach, it also investigates the redistribution effect of the reform amongst categories of consumers.

To do so, this chapter considers the conditional average effect of CRMs implementation and forward period set up over the time span while controlling for market fundamentals. An original database including 17 US states and 8 European countries over 24 years is computed. The research question opposes systems with CRMs to those without. This leaves numerous intermediate market designs such as strategic reserves or long-term capacity obligations out of the scope of this study. Using a differenced model, CRMs are found to leave industrial end-user prices unaffected except in the US where the conditional effect on prices is negative by up to 1.13% (US). The deflating effect of CRMs is only significant in this region, no evidence of prices being impacted appears in the European panel, nor in the pooled panel of the two regions. Contrary to intuition, the existence of a forward period in the US does not increase cost-efficiency. With respect to cost allocation, the most straightforward way to set out structural differences between the two prices is to investigate the evolution of the ratio of industrial end-user power prices over the residential ones. The former is expected to be less sticky than the latter. Results also show evidence of price convergence between residential and industrial end-user prices following the implementation of CRMs. If residential prices remain significantly higher than the industrial ones, CRMs tend to bridge the gap: potential price decrease benefit more to residential end-users than to industrial consumers. Further, results set out the relative price responsiveness of the consumer categories to market fundamentals as well as the inflating effect of renewable integration for end-users.

The remainder of this chapter is organized as follows. The next section provides a theoretical background to set out the costs and benefits of CRM implementation. Then, section 4.3 discusses the construction of the database and the methodology. Section 4.4 naturally presents the results while section 4.5 proposes a critical discussion of those

⁶Reasoning in terms of net costs (end-user prices) requires the implicit hypothesis that SoS is unaffected.

results. Ultimately, section 4.6 concludes this chapter.

4.2 Conceptual Background

4.2.1 CRMs as a precaution: costs and benefits

In the 80s - 90s, the general movement towards liberalization and deregulation reached power markets: monopolies were suspected to over procure capacity for not bearing the investment risk. The structure of the industry changed drastically. It went from regulated vertically integrated monopolies with important economies of scale, to competitive market segments in generation and retail.

In an efficient EOM, prices reflect the actual scarcity on the market and drive optimal entry and exit of production units [Stoft, 2002]. They also naturally provide incentives to be available when electricity is scarce to capture the highest prices. Unfortunately, a number of distortion ranging from non-linear costs to actual market imperfections prevent real-life electricity markets from providing optimal outcomes (see Cramton and Ockenfels [2012]; Keppler [2017]; Bublitz et al. [2019]).

If this drawback is common to all markets, the particularities of electricity as a good generate specific concerns. Mainly, electricity is non-economically storable while demand remains mostly inelastic and isolated from price signals as of now⁷. In this context, an instant balance between supply and demand is necessary, and this burden still lies on the supply-side: having sufficient available capacity to meet the demand is one of the key elements of SoS. In other words, inefficient investment incentives might generate important welfare losses through consumers' curtailment –independently from their preferences.

The solution proposed to make sure enough capacity is invested in is to implement CRMs. As with any market intervention, CRMs are likely to generate a dead-weight loss because the public authority is not perfectly informed in real life. The reason why doubt remains on whether CRMs are actually welfare improving, compared to the EOM, is that empirical assessment of their respective inefficiencies is close to impossible. In this context, CRM implementation lies on the *hypothesis* that the deviation from optimality is lower in this framework compared to any alternative market design. This might be due to a belief that investors are risk-averse and/or that consumers highly value SoS. In other words, the public authority considers the social costs related to the risk of shortages as being too high compared to the cost of enhancing SoS via a CRM. CRM implementation is thus a precaution, rather than a perfectly informed decision.

As discussed in the general introduction and chapter 2, CRMs effectively correct potential market imperfections. Mainly, they seek to limit the dependency of investment incentives

⁷This situation is quickly evolving with smart metering and efforts to develop demand response. However, a fully flexible and elastic demand is not expected to emerge in the short term for technical and political reasons.

on the rare extreme events with tremendous uncertainty that trigger high prices⁸. Capacity is given intrinsic value through CRMs [Oren, 2005]. Investment incentives do not solely rely on scarcity pricing anymore since profits include both an energy and a capacity component. Prices are less volatile and overall lower on the wholesale market [Bajo-Buenestado, 2017]. In industries with incomplete hedging possibilities as the electricity markets [de Maere d'Aertrycke et al., 2017; Newbery, 2016], reducing price volatility lowers the market risk which drives investment costs (see the following frame for a discussion on the role of risk). Besides, risk-averse agents are more likely to invest [de Vries, 2004].

Role of risk

The new market organization drastically changes the structure of market revenues. Where peakers used to recover their fixed and investment costs through a scarcity rent, they rely on capacity remuneration instead. Wholesale price variance decreases^a thanks to limited price spikes: the market risk is reduced, so is the total investment cost. To exemplify, let's consider an investor in a world where investors make their decision according to the net present value (NPV) criteria. Every investment with a positive NPV (expected to be profitable) is carried on^b and price volatility is the only source of risk driving investment costs up:

$$NPV_{inv}^{EOM} = \sum_{i=1}^T \frac{CF_i^{EOM} - C_i}{(1 + r^* + r_p)^i} - I \quad (4.1)$$

With T being the technical lifetime, I the investment cost, C_i is the annual fixed costs, CF_i^{EOM} the total annual cash flow in an EOM. r^* is the risk-free interest rate while r_p is the risk premium^c. All arguments are positive. Under CRM, investment cost recovery does not rely on the volatile scarcity rent anymore. Therefore, the risk premia disappears^d:

$$NPV_{inv}^{CRM} = \sum_{i=1}^T \frac{CF_i^{CRM} - C_i}{(1 + r^*)^i} - I \quad (4.2)$$

Consequently, if $CF_i^{EOM} = CF_i^{CRM}$, then $NPV_{inv}^{EOM} < NPV_{inv}^{CRM}$. More projects get invested in when a CRM is implemented and the reserve margin is naturally increased^e. Under a market organization with capacity remuneration, the investor decision rule does not change, but the NPV of given investments is more likely to be positive, all things equal.

Although considering CF_i^{EOM} equals CF_i^{CRM} is a common hypothesis since Joskow

⁸This mode of operation excludes strategic reserves which rather plays in the scarcity rent (see the general introduction and section 4.2.2).

and Tirole [2007], it remains a strong assumption. With a CRM ensuring peakers' investments and fixed costs recovery, wholesale prices do not have to rise as much anymore. Both volatility and price levels are reduced [de Vries and Heijnen, 2008], the net effect of CRM is uncertain and its implementation solely relies on the regulators' beliefs.

^aSee Hach et al. [2016] Hary et al. [2016]; Cepeda and Finon [2011]; de Maere et al. [2017]; de Vries and Heijnen [2008]; Bajo-Buenestado [2017]; Brown et al. [2015].

^bAs it is usually the case in agent-based models as EMLab-Generation or Power ACE models.

^cThe risk premium depends on investment-specific risk, which itself relates to the volatility of expected revenues

^dFor the sake of simplification, we consider that it disappears, but it most probably only reduces.

^eReserve margin: share of capacity that exceeds the expected peak demand.

Conceptually, the two market organizations discussed above represent the two extremes of a range of possible market designs. Under the EOM, plant revenues rely on the volatile scarcity rent while CRMs are implemented as a precaution to stabilize revenues and incentivize investment. Because CRMs are mainly a precaution, they have been both implemented as a palliative to a dysfunctional EOM⁹ and as the preferred market design for a liberalized electricity market¹⁰. On the other hand, even the most market-oriented electricity markets do not function as a theoretical EOM [Joskow, 2010; Oren, 2005]. The lack of empirical benchmark prevents from a quantitative assessment of the respective benefits of each market design. However, CRM implementation still represents a rupture *within* the market design of a given system: the public authority has chosen precaution over the "invisible hand".

In this sense, this chapter does not specifically oppose CRM and EOM. It rather compares the total system costs of designs with CRMs to alternative market designs, and more specifically to those historically anterior to CRM implementation in the different systems considered.

4.2.2 Taxonomy

As discussed, the implementation of CRMs is a precautionary measure considering that optimal reliability cannot be effectively quantified. If for some reason, the regulator believes the investors to be risk-averse, a CRM would alleviate risk and restore optimal investment. Similarly, when consumers are expected to highly value the security of supply¹¹, the regulator would be willing to limit potential blackouts by setting up a CRM. Several kinds of CRMs have been tailored, the design of the CRM itself is driven by the relative cost of each security of supply related market imperfection into the regulator's

⁹As an exception, Italy did implement a CRM following the 2004 blackout (see section K.2). MISO and Colombia are other examples of such behavior (refer to chapter 1).

¹⁰See the history of CRM implementation PJM, ISO-NE, NYISO, Ireland, Spain in section K.2.

¹¹Most consumers are price-taker and do not have access to real-time prices. They are then unable to send a signal on their preferences for the security of supply. Reliability being a public good, they have an incentive to reveal their preferences.

expectations (see chapter 1).

In most studies, CRMs designs are classified depending on the way the price is set and to whom it is granted. Straightforwardly enough, a quantity-based CRM requires the amount of capacity to be predefined while the price can vary against the supply. Price-based is the opposite. The price is set and the quantity is left to the market to decide. Ultimately, the CRM implemented can either be targeted when only selected units receive the remuneration or market-wide when all of them are to get paid for capacity. The literature usually recognizes five types of CRMs: capacity obligation, capacity payments, strategic reserve, capacity auctions, and reliability options [Henriot and Glachant, 2014; Meulman and Méray, 2012; de Vries, 2007].

The strategic reserve is excluded from the scope of the study for being a targeted, out-of-the-market, capacity procurement. Indeed, in such a CRM construction, plants joining the reserve cannot participate in the energy market anymore; they only get activated in times of scarcity by the regulator in exchange for cost recovery. It is considered as a CRM because it does secure capacity in order to increase the reserve margin. However, the strategic reserve does not actually correct any of the potential market imperfections and having additional energy produced out of the market at scarcity might even lower the scarcity rent and investment incentives.

Another kind of CRM falls out of the scope: the reliability auction¹². Contrary to the strategic reserve, this is not due to its mode of action, but rather to its place of implementation (see section 4.3.1). Indeed, the main illustration of a reliability auction is the Colombian market for firm energy (Mercado de Energia Firme). It consists of a call option on the energy market usually procured through an auction. When the spot price gets higher than the strike price defined by the system operator (SO), the option providers must produce and pay back the difference between the spot and the strike price to the SO. The strike price thus works as a revenue cap.

This study, therefore, focuses on the three main alternatives, most commonly implemented in the US and the EU. Capacity payments have been the first CRM design to be implemented and are little by little replaced by reliability or capacity auctions or obligations worldwide. Under capacity payments, the regulator estimates the complementary remuneration needed by the actors for the reserve margin to be optimal¹³. Such a payment is then dealt amongst generators depending on pre-defined parameters, often their availability at peak. In our panel, Spain and Portugal did keep capacity payments for a long period although reforms have been implemented through. Ireland has had a capacity payment implemented since 2007. The market operator calculates the missing money of a new peaker, which, multiplied by the available capacity at peak, makes the total sum of capacity payment. This amount is then redistributed amongst generators depending on

¹²This statement needs to be nuanced because ISO-NE recent designs are commonly (but not unanimously) considered as a reliability option Cramton et al. [2013].

¹³Reserve margin: expected total available capacity at peak divided by expected peak demand.

their forecasted availability, participation to loss of load probability (LOLP) reduction as well as their realized contribution to the latter.

In a capacity market, the regulator centrally procures a targeted level of capacity. For instance, in the PJM, the capacity demand curve is determined by the regulator through a predefined process, the market clears where the supply curve meets the demand curve. When decentralized, retailers have to secure their supply in order to be able to meet their peak in the future (former PJM). Those designs work in a similar fashion, to the point that they are sometimes considered as equivalent: they could be able to generate equivalent market outcomes under specific assumptions [Weitzman, 1974]. The remainder of this chapter will thus consider them indifferently to gain statistical power.

Compensating for this simplification, an additional feature is here considered of interest: the existence of a forward period. This specific feature is little studied in the literature and present a temporal variation: the forward period is often implemented as an upgrade compared to the previous CRM design. As such, it is less likely to weaken statistical power compared to differences *between* the systems –i.e. high-level features (see chapter 1). This is thus easier to account for in this analysis. The amount of available installed capacity in a given system can follow two complementary strategies: ensuring availability via demand-side management, storage, demothballing, etc, or favoring commissionings. A momentary restoration of expected revenues enhances overall availability in the system. However, for new investments, the investor needs to be reassured not only for the short term but he also wants to hedge market risks as much as possible on the investment horizon. Without a forward period, remuneration will only be granted once the decision to invest (the risk) is taken. Short term designs are also known to be more easily modifiable adding up regulatory uncertainty. The forward period allows market participants to secure part of their revenues in advance and, more importantly, before the investment is completed. In addition, the capacity market clearing transparently provides information on capacity needs. Such information tends to reduce investment cycles as shown by Ford [2001]. Capacity remuneration is not secured for the investment lifetime, but yet, it lowers revenue uncertainty for the investor [Pfeifenberger et al., 2009]. This makes a quite significant difference in terms of investment incentives. Unfortunately, this evolution is quite recent and has been implemented along with other improvements in the different states of the US. Indeed, the CRM version from the end of the nineties lacked obligations and gave limited incentive to invest due to the very short term framework (daily products) and the related capacity price volatility.

In this sense, this chapter uses the term "CRM" in a more restrictive way than most commonly used (see Meulman and Méray [2012]; CIGRE [2016]), mainly excluding strategic reserve. This is not without consequences on the empirical strategy. Mainly, the systems with "intermediate" market designs (i.e. which improve reliability through alternative design options) are disregarded. This quite naturally limits the geographical scope of data collection since the considered designs are mostly implemented in the US and the

EU –and thus exclude other regions including South America.

All in all, the net cost of CRMs is not straightforward as it impacts market dynamics through three possible channels: the cost of security of supply internalization (payments for capacity), the reduced energy prices and lower perceived investment risk. In addition, the extent to which each of these vectors of transmission are efficient remains empirically unassessed. Yet, CRMs are imposed on agents independently of their actual willingness to pay. To set out the net impact, end-user prices evolutions are analyzed on the ground that end-users are to pay for every cost component of electricity, whatever the market organization.

4.3 Data and Methodology

4.3.1 Variables and sources

To the author's knowledge, no consistent database is available at the power system level. Aggregated homogeneous national data are usually published by the IEA, but the country scale is not always the relevant degree to efficiently study power markets, especially from a regulation perspective. For instance, the North American power sector comprises a diversity of coexisting power systems with distinct market organizations. It seems natural to consider them at the state rather than the country level as in Joskow [2006] and Swadley and Yücel [2011]¹⁴. Although this provides a more accurate view, the pool-based organization of US markets does not follow state borders, meaning that utilities within a state are confronted with the same law, but not necessarily the same market rules. In this sense, there can exist discrepancies between the end-user prices within a given state. To tackle this aggregation bias, only states that are within a given system in their outstanding majority will be included in the panel. For the same reason, states displaying significant changes in the pool membership of their utilities over the period are naturally excluded.

The research question polarizes reality by opposing CRMs and other market designs. As discussed in section 4.2.2, the focus is set on a subset of CRMs expected to be more homogeneous. With this respect, Europe and the US are the two regions where CRMs have been mostly implemented and discussed. The geographical scope could be extended, but this would be to the expenses of other statistical issues, mainly a poorer identification. In this sense, the exclusion of "intermediate" solutions¹⁵ contributes to the homogeneity of the panel. However, it also further limits the size of the panel. Similarly, Colombia appears as a good candidate for our purpose, but it is also excluded as it would be the only South American country. This would both require resorting to additional data sources and limits the possibilities to control for potential regional specifics.

The database is built relying on different sources in order to have the desired level of

¹⁴Both examine state-level panel to assess the impact of liberalization reforms on end-user prices.

¹⁵Capacity requirements such as in CAISO or long term contracting as in Brazil can be considered as such.

detail for both US states and European countries. The in-depth analysis of existing CRMs (see section K.2 and chapter 1) combined with the constraints of publicly available homogeneous data¹⁶ lead to a rather macro panel (yearly data) of 25 states / countries over the period 1991-2014. The 25 states (17 US states and 8 European countries) composing the panel are: France, Belgium, Germany, the United Kingdom, Ireland, Spain, Portugal, Italy, states part of the ISO New England system (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont), of the PJM (Kentucky, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia), of Southwestern Power Pool (Kansas, Nebraska, Oklahoma) as well as Texas (ERCOT) and the state of New York (NYISO). Among those, only the UK, Ireland, Spain, Portugal, Italy, ISO-NE, NY-ISO, and the PJM have implemented a CRM at some point. The remaining systems are included to improve the role of control variables: they will be denoted "EOM" in the subsequent section, although this is a simplification.

The variables of CRM implementation (CRM and Forward) are self-constructed. Although CRM design is an ongoing learning process, the variable accounting for CRM implementation (CRM) is modeled as a dummy. It thus measures the average conditional effect of CRM implementation on end-user prices, leaving the ideas of price inertia and market convergence for further research. It is based on each country or state's regulation analysis and takes the value 1 the first year plants actually receive the capacity remuneration¹⁷. Afterward, the variable remains at the same level until capacity remuneration is eventually removed. In this panel, only the UK has ever removed a CRM, other systems upgraded theirs with additional features. As discussed, CRMs are considered as having a fairly homogeneous effect for the purpose of this rather macro analysis. However, one design feature stands out of the lot: the procurement lead time. As discussed in chapter 1, this has been one of the main changes in CRM designs. Indeed, for a forward period to have a hedging effect, it needs a minimum duration allowing investors to anticipate market evolution. ISO-NE and the PJM have added a forward period in the late 2000s while the UK, France, Italy, and Ireland are just implementing it¹⁸.

The discriminating criteria between a forward and a short term mechanism is the length of the lead time. Is considered as forward mechanism any CRM with a forward period of at least a year. The two explanatory variables interact as follows: there is one dummy accounting for CRM implementation and a second one for the existence of a forward period. The two dummies are also lagged (one year) to account for a potential delayed effect. Such a delay is suspected for two reasons: first, the full effects of a structural change like CRM implementation might take time to spread. Second, it is not uncommon for delivery periods to have a weather-related beginning. For instance, ISO-NE procures capacity from June to May, so the cost of capacity this first year of implementation is

¹⁶See chapter K for a detailed description of the data sources.

¹⁷For the Forward CRM, the relevant date is the first delivery year.

¹⁸See section K.2 for further information on the status of CRM implementation in the different countries of the panel.

likely to be lower¹⁹. In other words, while the dummy CRM (resp. Forward) starts the first year capacity is paid for, it might not concern the whole year and could underestimate the effect. The lagged variables (CRM1 and Forward1) aim at capturing those potential retarded effects. Mainly, if the two of them (either CRM and CRM1 or Forward and Forward1) display coefficients of opposite sign, it suggests that positive and negative feedback of the change in regulation might affect end-user prices within a different time frame. Otherwise, it indicates a progressive pass-through that would be natural under the second explanation.

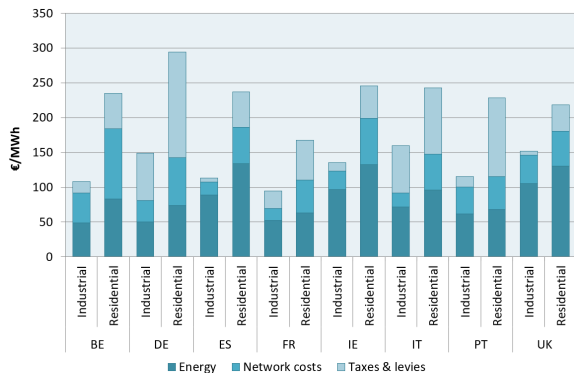


Figure 4.1: Breakdown of end-user electricity prices including all taxes and charges in some European countries in 2015 (data: Eurostats)

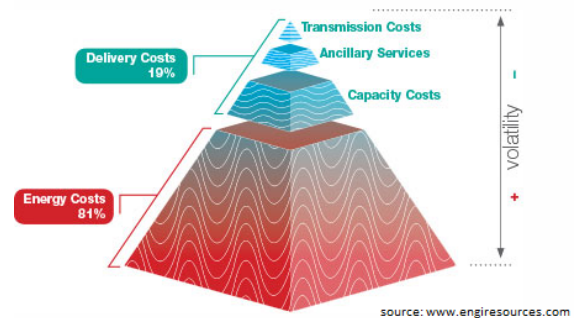


Figure 4.2: Breakdown of US end-user electricity prices (January 2014)

This analysis investigates whether market designs with a CRM are more costly than their counterparts (mainly their predecessor). In this sense, it seeks the aggregated effect of such a choice: the net cost. end-user prices are the only aggregate likely to reflect all costs component of electricity and as such, provide a view on the net cost. In the EU, end-users are currently presented as having three cost components (Eurostats): an energy component, based on the wholesale price, a transport component (network costs) and the taxes and levies (figure 4.1). This last category usually gathers miscellaneous elements ranging from subsidy pass-through to green tax. The cost of CRMs should also lie in this last component, but it might as well be accounted for differently in some countries. Figure 4.2 displays a similar breakdown for the US. Unfortunately, data available in the two regions do not provide such a breakdown by cost component over long enough periods, which would have provided ground for a more detailed analysis of the costs and benefits of CRMs, in addition to the net cost.

An interesting feature from figure 4.1 is that each component is not spread alike amongst categories of consumers (see figure 4.1 in appendix chapter L). This is driven by inner differences in the bargaining power of end consumers with retailers and politicians. Indeed, they all have good reasons to be protected against high prices: residential consumers are captive and inelastic, exposed to energy poverty while industrial ones have some

¹⁹Actors are also learning how the mechanism works and might not behave optimally.

| Variable ²⁰ | Variable name | Description | Type | Expected impact |
|-------------------------------------|---------------|-------------|-----------|-----------------|
| Real Industrial Power price | Price_Real | \$ /MWh | Dependant | - |
| Real Residential Power price | ResPrice_Real | \$/MWh | Dependent | - |
| Ratio Industrial/Residential prices | RatioIndRes | \$/MWh | Dependent | - |
| CRM implementation | CRM | Dummy | Interest | Positive |
| Lagged CRM | CRM1 | Dummy | Interest | Positive |
| Forward implementation | Forward | Dummy | Interest | Positive |
| Lagged Forward | Forward1 | Dummy | Interest | Positive |
| Real Gas price | GasPriceReal | \$/GJ | Control | Positive |
| Hydro generation share | HydroProd | % | Control | Negative |
| RES generation share | ResProd | % | Control | Negative |
| Nuclear generation share | NukeProd | % | Control | Negative |
| Coal generation share | CoalProd | % | Control | Negative |

Table 4.1: Variables

bargaining power and are subject to international cost competition. Consequently, the focus will be on industrial end-user prices rather than residential because they are driven by the energy component and thus respond to market dynamics easier to quantify –and to control for. Yet, the question of cost allocation remain of interest and will be investigated by computing the ratio of industrial end-user prices over residential ones. Following Hyland [2016], industrial electricity prices in the EU are the ones faced by medium-size firms. In the US, the Energy Information Agency is the primary source of per state data for the US. Industrial electricity price series are published industry-wide (not by size) and calculated for each state.

As illustrated in figure 4.1 and 4.2, energy costs represent most of the price paid by end consumers. As such, control variables will focus on capturing energy price drivers. They will be controlled for by market fundamentals: the generation mix of producing technologies and their respective costs are compiled as control variables (table 4.1 sums up the variables). However, the related coefficients are unlikely to display great significance due to the very short term nature of the wholesale prices that drive the level of the energy cost for end-users. Indeed, the stickiness of end-user prices tends to decorrelate their evolution to those of wholesale prices. Given the uncertainty of those, end-users usually face fixed rates based on their retailer’s expectations. This is to be accentuated when considering rather aggregated data (yearly).

The generation mix is a powerful price driver for electricity wholesale prices, which, on average, represents up to 80% of the final bill according to figure 4.2. Indeed, electricity prices vary from an hour to the other depending on supply and demand instant conditions. The marginal technology at any point in time will thus compose the base calculation to obtain the average cost of energy over the year. Unfortunately, this is a piece of information that is often unpublished, and even less in the 90s. A proxy often used to

²⁰See appendix chapter K for additional information on variables.

measure the costliness of a system is the generation mix: the cheaper technologies are used to generate over the year, the cheaper the average price is expected to be. This differs from knowing the marginal technology in that a unit can produce in every single hour in the year and yet, never set the price, thus not driving the prices downwards. Reasoning in terms of technology thus limits this drawback because those who have limited generating capacities are unlikely to be setting the price for a large number of hours due to the important volatility of the (residual) demand. In addition, the marginal plant is often either gas or coal-fired, meaning that electricity prices are, at least partially, driven by the variation in the price of these primary sources of energy. As highlighted in Hyland [2016], data availability does not allow for the inclusion of coal prices, but the high correlation between the two time-series makes the exclusion of coal prices less of a problem.

The model will thus include the share²¹ of generation from (i) hydropower, (ii) renewables –RES–, (iii) nuclear and (iv) coal as well as the (v) gas prices to the industry to account for energy price drivers. Using shares instead of actual generation normalizes the data to avoid bias towards bigger countries or states. The average cost of renewable technologies has a null marginal cost but their intermittency generates stress in the power system. On the contrary, hydropower usually has a stabilizing effect on prices given there is enough water storage. Nuclear generation is cheap but little flexible while coal plants are mid merit technologies, both more flexible and expensive than nuclear. All of them are expected to have a deflating effect on end-user prices although the contrary would not be too surprising for renewable and coal shares. Gas plants often being marginal, it does make sense to consider its fuel cost instead of its share in total generation. Due to the unavailability of long series on gas prices to the power sector, industrial gas prices are used as a proxy.

In line with the dependent variable (and data availability), the medium size firms gas prices are used in Europe. This data is also available on Eurostat. As for the US, industrial gas price series are industry-wide but calculated for each state (EIA). Missing data have been filled using variations. Information on the electricity mix is gathered from the IEA series on electricity production by fuel and country, the American states' production mix can be download from the EIA. All price series are converted into real dollars, a more detailed description of the database is available in chapter K.

4.3.2 Descriptive statistics

Table L.1 and L.2 (in chapter L) provide an elemental description of the dataset. The panel seems rather heterogeneous in terms of generation mix as the standard deviation is high compared to the mean and even higher in some cases. The presence of individual effects is confirmed in chapter L that display important time-invariant discrepancies between the different states/countries. This is fairly intuitive; each country has the generation mix matching its natural endowments and demand shape (see chapter 1). Common methods to deal with individual effects include demeaning or differencing the data (see also table L.1

²¹Productions per fuel become shares when divided by the total production.

and L.2 to be convinced that first differences do remove individual effects in the dataset). However, this section will focus on the data in level that motivate the choices in terms of methodology: regression in differences. In this sense, the data is displayed both in differences and level.

Interestingly, industrial consumers pay an average annual price 35% lower than residential consumers, reflecting both the negotiating power of industrial consumers compared to residential ones and their finer view on their load's shape. This is consistent with economic theory as residential customers are both more captive and with less bargaining power, comforting the choice of industrial end-user prices as a variable of interest.

Coherently with the hypothesis of sticky residential power prices, the ratio should be driven by industrial end-user price variations, figure L.2 and L.4 show such a relationship. Each state/country has both a different price level and standard deviation over time, suggesting strong individual effects. The private and public choices in terms of cost allocation discussed earlier is reflected in the dissimilarities between figure L.1 and L.3. The upward trend of gas price average in figure L.6 echoes (in spikier) the real industrial power prices variations. Interestingly, gas prices tend to diverge over the period with an increasing standard deviation²². Simultaneously, gas price differences between the countries/states are very small compared with what is observed in end-user power prices. Assuredly, industrial gas price is a relevant price driver, but country specifics should complete the understanding of end-user power prices.

Table L.1 also presents statistics discriminating for states which implemented a CRM at some point. Statistically, the countries which decided to implement a CRM are different from the ones which declined the option. It is rather unsurprising considering the presence of individual effects. Indeed, those differences mainly disappear when the data is first differenced (see table L.2). The test for mean difference tends to support the hypothesis that end-user prices are higher in systems that decided to implement a CRM over the period (table L.1), even though this difference is not statistically significant when reasoning in variations (table L.2). Contrastingly, the standard deviation of industrial prices is somewhat similar for the two groups whereas the standard deviation for residential prices is 30% lower for the countries that did decide to implement a CRM (table L.1). Statistics suggest that residential customers under CRM are more protected against price variations than their counterparts that do not benefit from this measure: they have a lower standard deviation for a similar average price. Industrial consumers probably use their bargaining power so they can adjust better to wholesale price evolution. This observation confirms the interest of using industrial end-user prices as a dependent variable, and questions the cost allocation between the two categories of consumers. Gas prices are naturally similar under the two designs as they typically converge on a regional basis.

Figure 4.3 and 4.4 shows the shape of the relation between the variables. Mainly, reasoning

²²The statement remains valid at the regional level as well. It thus cannot be fully seen as a consequence of the shale gas revolution.

in variation normalizes the data and abstracts from time-invariant individual effect. All variables have a rather linear relationship with the logarithm of industrial power prices. Two-way representations of the control variables with industrial and residential power prices display similar patterns although the distribution of the dots is broader in the case of residential consumers. As suspected, the residential end-user prices are less responsive to energy price drivers. Hydroelectric production's share in total production along with nuclear share show no clear correlation with the logarithm of power prices at the pooled level. Considering they are both baseload technologies whose production depends mainly on installed capacity, it is rather unsurprising (see figure L.7, L.8, L.11 and L.12 for more information on the data structure). On the contrary, real industrial gas prices do present a rather positive correlation with end-user power prices as expected. Increasing coal production in the mix would somewhat lower prices; but this disappears when the data is first differenced (figure 4.4). The case of renewables is more peculiar: a higher share in the mix is positively correlated with end-user prices. Green technologies have benefited from important cost reductions during the period allowing for large scale development, although adoption rates largely depend on state support, be it on a regulatory or financial level (see figure L.14 and L.13).

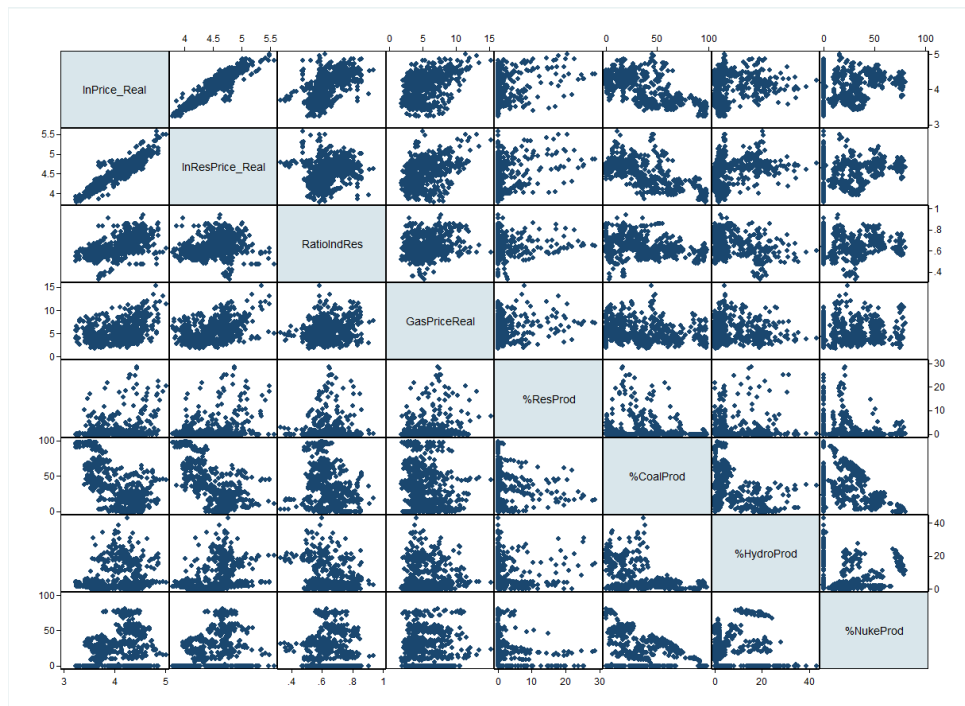


Figure 4.3: Two way plots of the variables in levels

4.3.3 Methodology

As discussed earlier, CRM implementation is exogenous from end-user prices because it depends on the public authorities' expectations on the risk aversion of investors as well as the consumers' preferences in terms of reliability. As an illustration, some systems

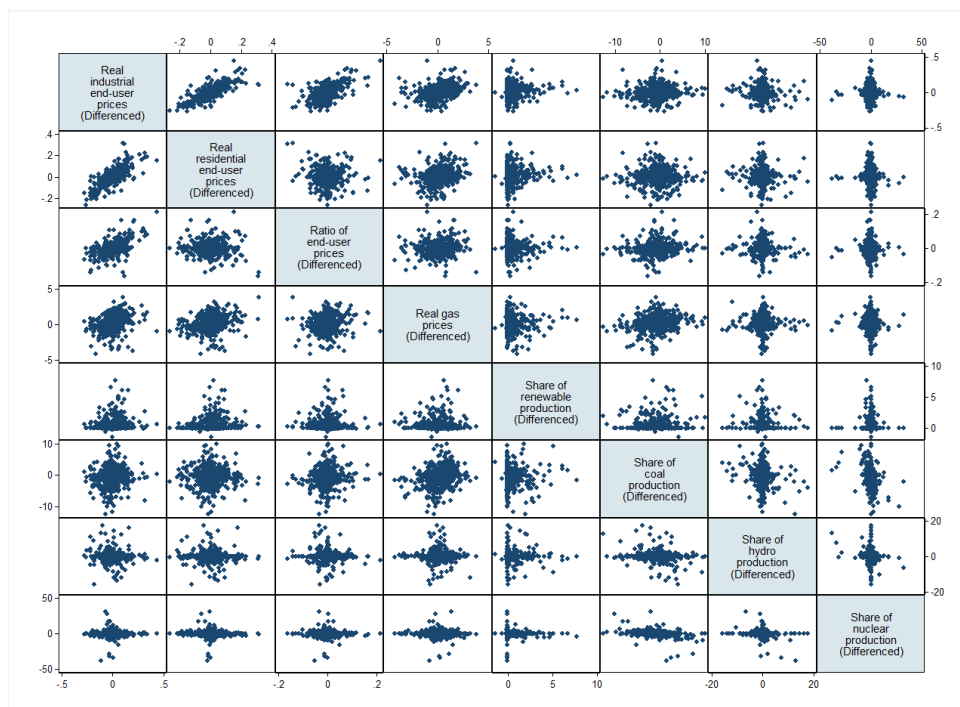


Figure 4.4: Two way plots of the variables in FD

have never functioned without a CRM since liberalization. The beliefs on investors and consumers' preferences are thus supposed exogenous to the regressors. Without perfect information on those, it is difficult for the public authority to conclude on whether there is a social benefit to the measure: the implementation is then based on the belief that the costs of inaction are higher than the costs of precaution. Similarly, the electricity mix (hydroelectric, nuclear, renewable and coal share in total production) can be considered as exogenous as they will mainly depend on exogenous factors (i.e. natural endowment). It is sometimes argued that high energy prices will induce additional investment, which is likely to modify the generation mix. However, this reasoning is debatable since investments are decided based on expected revenues (future energy prices), and not on realized retail prices the same year. In addition, this only applies to the energy component of retail prices. The descriptive statistics (see section 4.3.2) clearly suggest individual specificities, while there are also reasons to suspect the influence of common shocks on end-user prices.

The omitted variable bias is a natural concern when dealing with such a macro panel. Allegedly, individual and time fixed effects should be controlled for as well as spatial effects to capture most of those unobservable variables. Mainly, differencing is a rather natural way to dismiss fixed effects (FE). The preference for such a method over demeaning—which is a more common approach to FE—will be further discussed. Culture, preferences, and history or geographical proximity are examples of time-invariant individual effects that are to be controlled for in the model. In addition, there are good reasons to believe that there exist common shocks for neighboring countries. For instance, shocks on commodities prices, GDP or weather variations are likely to affect all European countries at once.

Similarly, the EU or FERC directives come into force at the same time for the whole region. The combination of individual and time fixed effects should control for most of the price drivers to provide a consistent estimate of the partial effect of CRMs on end-user prices. However, it remains difficult to defend the idea that the model would effectively hold everything else together because of (i) the macro level of the data and (ii) the imperfectly rational expectations retailers empirically form. This condition being necessary to defend strict causality, all results will then be interpreted in terms of expected effect for the sake of precision.

The same model is used to answer the two questions of interest: the net cost (or benefit) and its allocation. The dependent variable will be the only modification to the model. Firstly, the logarithm of real industrial end-user prices will be considered to set out the conditional effect of CRM implementation. This is to ease the interpretation of the coefficients. Secondly, the ratio of industrial end-user prices over residential ones will replace the level variable as a dependent variable to investigate how costs and benefits are allocated amongst consumers. The model will have the following form:

$$P_{it} = C_{it}\beta_1 + C_{it-1}\beta_2 + X_{it}\alpha + \sigma_i + \eta_{ij} + \omega t + \gamma_{rt} + \epsilon_{it} \quad (4.3)$$

P_{it} then represents either the series of (i) the logarithm of real industrial end-user power price in logarithm or (ii) the ratio industrial end-user power price over residential one in country i at year t and X_{it} is the matrix of the control variables as defined and described in section 4.3.1 and 4.3.2²³. Individual effects are embedded in σ_i while spatial fixed effects and regional time fixed effects are respectively represented through η_{ij} and γ_{rt} , r being the index that stands for Region (US or EU) and j the neighboring state. Conjunction is indeed different in both regions, justifying specific time effects. Finally, a time trend t is added to account for technical progress and the error term is ϵ_{it} . C_{it} is the set of CRMs variables as previously defined: CRM and forward along with their first lag. The coefficients then add up. Using dummy variables is a modeling choice: the coefficient reflects the average change in end-user power prices since implementation. Since the shape of the convergence toward a new equilibrium is unknown, the average effect is assumed to be flat and constant over the implementation period.

As expected, the robust Hausman test confirms the existence of individual fixed effects. Differencing equation (3) removes the individual effects²⁴ which are not time dependent and variables mostly become stationary. In a differenced model, the constant stands for a trend that is used to approximate technical progress²⁵. The following equation is then to be estimated:

²³To test for level effects, the exercise has been performed with prices in level and prices indices. The results are rather similar. The log level model has been chosen to ease interpretation.

²⁴BM-LM test rejects the presence of individual effects.

²⁵Including or not a constant does not significantly affect the regression results (coefficients or significance levels) when logarithm of the real industrial end-user prices are the dependant variable.

$$\Delta P_{it} = \omega' + \Delta C_{it}\beta'_1 + \Delta C_{it-1}\beta'_2 + \Delta X_{it}\alpha' + \Delta \gamma'_{rt} + \Delta \epsilon_{it} \quad (4.4)$$

A differenced model with OLS is preferred to fixed effects estimation to deal with individual effects. Indeed, the serial correlation disappears under such specification²⁶. However, evidence of heteroscedasticity and cross-sectional dependence remains so the reported standard errors account for the non-orthogonality of the error (Driscoll and Kraay standard errors) [Hoechle, 2007]. β'_1 and β'_2 would be interpreted as the average effect of CRM implementation on the real industrial power price in percent. If the coefficient is negative, the shift in surplus is quite straightforward: end-user benefit from additional or equal security of supply (by hypotheses) for a lower price. Their surplus increases with the introduction of a capacity remuneration mechanism and a market with CRM is a much better design than the alternatives. However, when the coefficient is positive, the financial costs overweight the financial gain at the end-user level. The coefficient for industrial real gas prices should also come out positive and significant while the hydro-electric share, renewable share and nuclear share should theoretically have a downward effect on prices as these kinds of generation are quite inexpensive. The coefficient for coal production could be positive or negative depending on all those elements.

As a first stage, the full model is estimated (Model 1). Further, the forward feature variable is excluded (Model 2) to assess how results are affected. Then, the two models are applied to regional sub-panels: European countries on the one hand, and US states on the other hand. Indeed, pooling state-level data with country-level data makes economic and statistical sense in order to have a large enough panel with variability in the data so that a global effect can be derived. But it is also a leap of faith that needs to be investigated at a more granular level: the panel is aggregated from different data sources, only US states have a forward period, European CRMs have been less profoundly reformed and the regulation history of the two regions is different. All those elements, as well as different data sources, might affect poolability in a way not foreseen by the Chow test. The described models will be run at a regional level to set out potential differences. When running the models at the regional level, only the American systems do have a forward period feature, Model 1 is irrelevant at the European level. Industrial and residential end-user power prices display similar results: only results corresponding to the former will be displayed. To complete the analysis in terms of distribution effect, the methodology is applied to the ratio of the two prices²⁷.

²⁶The two techniques have been developed for similar purposes: fixed effect estimators demean the data to remove the fixed effects while the first differences remove all time-invariant characteristics. The interpretation of coefficients is thus the same. The two methods are equivalent under two time periods. Under longer horizons, the choice between the two depends on the structure of error terms. Mainly errors should be serially uncorrelated [Wooldridge, 2001]. Another, less prevalent, reason to prefer first differences is that the FE estimator converges when n tends to infinity, which is far from being the case here.

²⁷The ratio of industrial over residential power prices cancels out some fixed effects. The global time fixed effects replace regional ones in that case.

4.4 Results

4.4.1 Capacity remuneration

The implementation of such a measure does not have a net inflating effect on end-user prices (table 4.2). If any, the effect would rather be negative as suggested by the results at the US sub-regional level. In a more economical sense, the decrease in wholesale prices more than compensates the costs associated with the new remuneration leading to a price decrease.

The insignificance of the effect at the pooled level is rather unsurprising considering the heterogeneity of CRMs in Europe and the level of state intervention. Indeed, over the first times of liberalization, governments have tried to protect their consumers, especially the most vulnerable ones. In a context of increasing European integration²⁹, the Spanish government took action against inflation by reducing electricity tariffs [Arnedillo, 2004]. The structural deficit in tariff structure has only been taking care of at the beginning of 2013³⁰. Under a framework of structural interventionism in end-user prices until recent times, strong results would require a broader and longer panel, including the most recent CRM experiences and regulatory changes in France, the UK as well as in Italy and Ireland.

On the contrary, the conditional effect of the implementation of a reliability standard through centralized capacity remuneration is a decrease of industrial end-user prices by 1.13% on average in the US states of the panel. The lagged policy variable does not have a significant effect. The amendment of such CRM in order to include a forward period does not significantly affect prices neither. The gains in efficiency that were expected through in-depth reform of the mechanism are not reflected on end-user prices, even though the underlying dynamics of investment and availability are very different under such a framework. This tends to oppose the hypothesis of greater efficiency of the forward mechanisms over the short term ones as if all the gains already kicked in with CRM implementation. In the European panel as well as in the pooled sample, policy variables do not stand out as significantly different from zero.

In a framework with two categories of consumers: the industrial and residential end-user, the distributional effect of a measure is of great interest. Results in table 4.3 suggest that CRM implementation creates a convergence between industrial and residential end-user power prices through a positive conditional effect on the ratio³¹. Indeed, the ratio is positive by essence and residential prices are higher than industrial ones at all times in all states (see figure L.3). Assuming CRMs do lower end-user prices (as suggested by table 4.2 and M.1), residential consumers would benefit more from the price reduction induced by CRM and forward period implementation than the industrial ones for the gap

²⁸Only countries which implemented a CRM are taken into account

²⁹Fixed exchange rates with the Euro were set at the end of 1998.

³⁰See the newspaper article *Deficit de tarifa o sobre coste de capacidad*, Andrés Seco, El País, 19 Dic 2016.

³¹The positive coefficient indicates that the ratio converges towards one, meaning that the two prices get closer one to another.

| | (1) | (2) | (3) | (4) | (5) |
|--------------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| | Model 1 | Model 2 | Model 2 | Model 1 | Model 2 |
| | Pooled | Pooled | EU | US | US |
| VARIABLES | $\Delta \ln(\text{Price})$ | $\Delta \ln(\text{Price})$ | $\Delta \ln(\text{Price})$ | $\Delta \ln(\text{Price})$ | $\Delta \ln(\text{Price})$ |
| ΔCRM | 0.000270 (0.0162) | 0.000147 (0.0162) | 0.00962 (0.0299) | -0.0113*** (0.00264) | -0.0117*** (0.00249) |
| ΔCRM1 | 0.0192 (0.0238) | 0.0190 (0.0237) | 0.0569 (0.0396) | -0.00426 (0.00587) | -0.00469 (0.00576) |
| $\Delta \text{Forward}$ | -0.00953 (0.0248) | | | -0.00966 (0.0220) | |
| $\Delta \text{Forward1}$ | 0.0506 (0.0424) | | | 0.0537 (0.0422) | |
| $\Delta \text{GasPriceReal}$ | 7.60e-05 (0.000209) | 8.33e-05 (0.000210) | 0.000173 (0.000187) | 4.29e-06 (0.000440) | 1.83e-05 (0.000438) |
| $\Delta \text{HydroProd}$ | -0.00116 (0.000800) | -0.00115 (0.000825) | -0.000634 (0.000795) | -0.00258 (0.00171) | -0.00232 (0.00177) |
| $\Delta \text{ResProd}$ | 0.00567*** (0.00190) | 0.00519*** (0.00159) | 0.00452 (0.00284) | 0.00793*** (0.00269) | 0.00689** (0.00302) |
| $\Delta \text{NukeProd}$ | -0.000430 (0.000445) | -0.000512 (0.000469) | -0.000642 (0.00398) | -0.000517 (0.000471) | -0.000603 (0.000495) |
| $\Delta \text{CoalProd}$ | 0.000538 (0.000883) | 0.000249 (0.00103) | -7.14e-05 (0.00215) | 0.000895 (0.000753) | 0.000429 (0.000781) |
| Constant | -0.00298 (0.00341) | -0.00317 (0.00342) | 0.0144** (0.00593) | -0.0106* (0.00562) | -0.0109* (0.00553) |
| Regional time fixed effects | YES | YES | YES | YES | YES |
| Observations | 575 | 575 | 184 | 391 | 391 |
| R-squared | 0.496 | 0.492 | 0.716 | 0.257 | 0.246 |
| Number of groups | 25 | 25 | 8 | 17 | 17 |

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.2: Regression results on industrial prices (1992-2014)

| | (1) | (2) | (3) | (4) | (5) |
|-----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| | Model 1 | Model 2 | Model 2 | Model 1 | Model 2 |
| | Pooled | Pooled | EU | US | US |
| VARIABLES | $\Delta\text{RatioIndRes}$ | $\Delta\text{RatioIndRes}$ | $\Delta\text{RatioIndRes}$ | $\Delta\text{RatioIndRes}$ | $\Delta\text{RatioIndRes}$ |
| ΔCRM | 0.00602 (0.00386) | 0.00576 (0.00385) | 0.0128 (0.00990) | 0.00278** (0.00130) | 0.00261* (0.00129) |
| ΔCRM1 | 0.0140** (0.00613) | 0.0135** (0.00584) | 0.0149 (0.0126) | 0.00628* (0.00325) | 0.00606* (0.00328) |
| $\Delta\text{Forward}$ | 0.0162*** (0.00400) | | | 0.0119*** (0.00404) | |
| $\Delta\text{Forward1}$ | 0.0129** (0.00464) | | | 0.0225* (0.0110) | |
| $\Delta\text{GasPriceReal}$ | -2.82e-06 (4.74e-05) | -4.01e-06 (4.82e-05) | 3.97e-05 (0.000117) | 2.02e-06 (0.000156) | 1.72e-05 (0.000145) |
| $\Delta\text{HydroProd}$ | -0.000661* (0.000329) | -0.000709** (0.000334) | -0.000508 (0.000552) | -0.000695 (0.000726) | -0.000761 (0.000740) |
| $\Delta\text{ResProd}$ | 0.00317*** (0.000834) | 0.00260*** (0.000839) | 0.00167 (0.00240) | 0.00380** (0.00174) | 0.00312* (0.00155) |
| $\Delta\text{NukeProd}$ | -0.000111 (0.000248) | -0.000126 (0.000248) | 2.31e-05 (0.00220) | -0.000156 (0.000312) | -0.000205 (0.000309) |
| $\Delta\text{CoalProd}$ | 0.000990** (0.000373) | 0.000903** (0.000355) | 0.000631 (0.000674) | 0.000796 (0.000574) | 0.000551 (0.000514) |
| Constant | -0.0101*** (0.000814) | -0.0102*** (0.000830) | -0.0121** (0.00389) | -0.00980*** (0.00204) | -0.0100*** (0.00192) |
| Time fixed effects | YES | YES | YES | YES | YES |
| Observations | 575 | 575 | 184 | 391 | 391 |
| R-squared | 0.144 | 0.139 | 0.225 | 0.188 | 0.177 |
| Number of groups | 25 | 25 | 8 | 17 | 17 |

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.3: Regression results on the ratio industrial prices over residential prices (1992-2014)

between prices to decrease. The effect is persistent and often hits harder with one year lag. This is due to residential price stickiness and is especially true for CRM implementation where only the lagged policy variable significantly affects the ratio. It holds to a lower extent for the forward feature implementation.

4.4.2 Electricity mix

Control variable coefficients are very little impacted by specification, their sign remains coherent with market fundamentals although mostly insignificant for the reasons discussed earlier. As meaningful price drivers, higher industrial gas prices are consistently linked to higher industrial power prices. Regarding hydroelectric production and nuclear, the coefficient is naturally negative. Both benefit from low marginal costs which tend to lower power prices on average. The insignificance was expected here because of the low variability of the hydroelectric and nuclear production in the time dimension. Indeed, Swadley and Yücel [2011] and Steiner [2001] also find the coefficients for hydroelectric production and nuclear to be insignificant respectively in the US and in a cross country study. Other than having a fairly intuitive sign, the effect of control variables remains too small to be considered as different from zero in all cases except renewables, whose positive coefficient is both unexpected and significant.

Indeed, increasing renewable penetration would have two contradictory effects on prices [Moreno et al., 2012]. A downward influence would be because of the so-called merit order effect. The upward effect kicks in when subsidies for renewable development and flexibility costs are passed through to the end-user. The inflating effect seems here to dominate. An increase of one point in renewable production increases industrial power prices by 0.06% on average and even 0.08% in the case of the US states. The effect is only significant at the 15% level in European countries, and the order of magnitude also supports this hypothesis³².

The regression on the ratio is instructive on the link between market fundamentals and end-user prices. Curiously, all the control variables in table 4.3 display coefficients of the same sign as in table 4.2. This backs up the hypothesis of stickier residential prices. Indeed, if a positive shock on industrial prices also reduces the gap between industrial and residential prices and distress in prices tears them further apart, the natural conclusion is that industrial end-user power prices are more responsive to market fundamentals than residential ones. The latter see market fluctuations averaged out rather than passed through at full variance, be it instantaneously or the next year³³.

However, this hypothesis does not hold for renewable production. Indeed, as stated above, the well-known merit order effect (downward effect on wholesale prices) is compensated at

³²This partially confirms and extends results from Moreno et al. [2012]. They find that an increase of 1% in the electricity generated from renewable sources (including hydro) as a percentage of total gross electricity production leads to a 0.018% increase in household prices in the EU-27.

³³Hypothesis tested but not discussed here: residential end-user power prices actually respond to contemporaneous market fundamentals and not their lagged value.

the end-user level by other cost components. It is then only natural that the stickiness of end-user prices compared to wholesale prices does not stand out. Instead, the coefficient reflects the net cost allocation.

4.4.3 Robustness

Table M.1 displays the results for residential end-user prices: they do not differ much from those of industrial end-user prices. The effect of CRM implementation remains statistically insignificant in all regressions except for the American panel. As the regression on the ratio suggests, the reduction in prices appears more important for residential than industrial consumers with an average decrease around 3%, half of it being passed through with a one year lag. The inflating effect of renewable production does not seem to affect residential end-users at all, supporting previous statements as well: when policies result from an institutional will, market fundamentals cease to be price drivers.

The size and heterogeneity of the panel do not allow for strongly significant results, but OLS estimators should converge towards their true value, so consistency among specifications results is an important verification to do. Indeed, table L.1 shows significant differences between the countries that decided to implement a CRM and the others, but those are canceled out in differences (table L.2), at the expense of lower variability in the data. In a long panel, the incorporation of time fixed effects largely affects degrees of freedom and consequently the standard errors. Similarly, the will to detect potential responses following the implementation of a forward period might create a spurious regression. Lastly, the UK is the only country to remove a CRM in the panel. It is consistent to consider the situation where CRM removal does not bring price levels back to their former level, but rather towards a new height. The UK is thus excluded from the panel for robustness. All those specifications are represented in figure M.1 to M.12. Overall, robustness checks confirm previous results.

Figure M.1 to M.6 present the regulation coefficients either under different specifications or with distinct standard errors. The reference coefficient (baseline) is the one from Model 1 as displayed in table 4.2 and 4.3. For both the logarithm of real industrial end-user power prices (see figure M.1, M.3 and M.5) and the ratio industrial over residential end-user prices (see figure M.2, M.4 and M.6), the baseline coefficient is displayed along with the Newey estimator, the cluster robust standard errors from OLS³⁴ as well as the modified model³⁵ removing alternatively the states which never implemented a CRM, the time fixed effects (TFE) and the UK. In general, results under the different specifications are rather consistent one with the other. The choice of standard errors is not determinant either. The Driscoll Kraay standard errors account for cross-sectional dependence contrary to the cluster robust and the Newey. None of the alternative regressions seriously question the results as all coefficients converge both in terms of standard errors and in levels. Even

³⁴Only standard errors differ between the three.

³⁵Using Dris Kaay standard errors.

taking a larger confidence interval (80%), the implementation of capacity remuneration struggles to give a significant effect but in the American panel.

4.5 Discussion

Lower end-user prices under a capacity remuneration framework are possible but theoretically improbable. This is why this option has been little discussed. As shown in section 4.2.1, the cost of capacity remuneration should be at least equal to the reduction in scarcity rent. CRMs also alleviate market risk, favoring investments. None of these elements drastically impact prices. But relaxing the assumption that $CF_i^{EOM} = CF_i^{CRM}$ from section 4.2.1, prices become an adjustment variable. Instead of maintaining the revenues of plants, the regulator might decide to maintain the reserve margin. When the official argument of the precocious regulator to implement capacity remuneration is that the missing money creates risks on systems' security of supply, a target in terms of reserve margin is highly probable³⁶, even though the security of supply was never actually in danger. In that case, the remuneration of the plants does not have to be as high as under the EOM. The market risk decreases, and so does the expected return on investment. Achieving the same reserve margin as under the EOM results less costly.

Comparing with numerical models, the main difference is the scarcity pricing: in real markets, prices never even get close to the VoLL. Markets without capacity remuneration do not value reliability per se. It then comes naturally to mind that the internalization of the security of supply will be costly. And yet, the whole argument around CRMs is about the very low probability of blackout even without CRMs: is intervention needed? To account for the social cost of blackout, most numerical models price scarcity at the estimated VoLL (usually higher than 1000€). This makes the underlying hypotheses of the two approaches fundamentally differ, yet this points to similar intuitions. de Vries and Heijnen [2008] find that under demand uncertainty, all types of CRM lead to lower prices (capacity plus energy) than the EOM. With and without a CRM, markets rarely reach the scarcity price of 8600 €/MWh used in their study (although it might be needed), which tends to question the empirical reach of such results. However, present results also suggest that prices might decrease, implying a potentially strong effect of uncertainty and risk on system costs. Both results seem to support the idea that the risk factor is undervalued in CRMs' assessments. For instance, the DECC estimates the net cost of the first auction will be £2 while the gross cost is more around £11. The DECC foresees a strong reduction in energy prices, leading to a 9£ difference between the gross and

³⁶Considering the reserve margin not to be a variable of adjustment is a credible hypothesis both because security of supply is rarely actually at risk, and the reserve margin does not show structural evolution under the different market designs.

net cost³⁷. This represents a 1.3% increase³⁸, an order of magnitude that lends in the confidence interval of the present results (see figure M.3).

Energy poverty is a growing political concern in developed countries as lifestyle increasingly relies on electricity. Decision-makers seem to have addressed the problem reducing the relative burden borne by residential consumers. Indeed, results suggest an implicit decision to favor residential end-users by reducing the gap between their prices and those of industrial consumers. This holds both for CRM implementation and renewable integration. It might raise concern on competitiveness in the long run if industrial end-users are structurally penalized compared to other groups of consumers.

The ongoing debate on capacity remuneration has mainly gravitated around the concept of security of supply as an externality, the efficiency of the benchmark model (EOM) and the need to correct given imperfections. The three main effects of CRMs according to the theory are the cost of capacity remuneration itself combined with the expected wholesale energy price decrease and the diminution of risk premium. The only way to assess the joint effect of those is through global system costs, here approximated by end-user prices. Present results give a broader dimension to the argument suggesting that CRMs are probably neutral in terms of costs, and even potentially financially beneficial to end-users compared to the previous regulation. If further research proves this result to be true using the EOM as a benchmark, the debate about the EOM's efficiency becomes irrelevant. However, those results have to be taken with caution as no causal relationship is proven with this study. At the macro level, many interactions are possible and it is impossible to control for all of them. For instance, end-user prices are the only metric that could give a net effect of CRMs, but it is also an aggregate subject to numerous social, economic and political forces that are difficult to account for. In addition to energy prices, end-user prices include transport costs and taxes and levies. Using this aggregate is a way to make sure the capacity costs and benefits are included. As a drawback, structural changes in transport costs or taxes and levies are not controlled for due to lack of information.

Moreover, the estimator works in the *within* dimension, while a significant number of the considered systems have never had an EOM. In this sense, the results highlight a change with respect to the previous design rather than the EOM. The pooled panel reflects a diversity of situations, and a non-significant coefficient might indicate that CRMs are neither better nor worse than their counterparts. In the case of the US, however, all considered systems have implemented a design with a CRM straight away after deregulation. This means that the conditional reduction of end-user prices indicates a benefit from the deregulated market design (with a CRM) compared to the previous design (also cautious). Even if it does not inform on the relative performance of CRMs

³⁷The total cost of the auction being £0.96bn (in 2012 prices), DECC estimates the average gross cost per household to be around £11 for the year 2018 (first delivery year). When including wholesale price reduction, the net cost goes down to £2.

³⁸Household prices in 2015 were around £150 including VAT according to Eurostats.

compared to the EOM, it still suggests gains compared to the regulated situation, meaning that CRMs do not equate a regulated situation.

4.6 Conclusion

Capacity remuneration is quite controversial. It is broadly admitted that the EOM is the first best equilibrium under perfect competition. However, electricity markets are also commonly recognized not to operate under such circumstances and no consensus has emerged so far on the second-best. Meanwhile, more and more CRMs are being implemented. After the first learning phase, east US regulators acknowledged the limits of the initial short term mechanisms in the mid-2000s and made the necessary adjustments (chapter 1). All capacity schemes based on "installed capacity" have been turned into "available capacity" based mechanisms. Price-based mechanisms are being changed for volume-based ones and more and more systems go for a forward period. Now, such evolution is also being implemented in Italy, Ireland, the UK, and France. Although current evolution indicates a consensus on some key features of CRMs, the links with the relevant market failures remain blur which toughens efficiency assessment. The efficacy of a CRM appears through two different channels: price efficiency and security of supply efficiency.

Contributing to the literature on the first element, this study finds weak evidence of a partial effect of CRM implementation on real industrial end-user power prices, which tend to decrease on average. Indeed, no statistical effect appears in European countries or when pooling US states with European countries. However, real industrial power prices conditionally decrease by 1.2% per year in US states on average. Contrary to expectations, changes to improve CRM efficiency result equally costly for end consumers as the implementation itself. The reforms of CRMs in the US implemented simultaneously a forward period, changes in the demand curve and more stringent criteria on availability without seemingly affecting price levels. It is as if neither the increased obligations nor the forward faced by producers conditionally affect prices. The most logical inference is consequently that it did not affect their costs because the incentive to produce at peak has always existed, be it in EOM or under CRM. Unfortunately, too few systems have implemented the forward period so far to truly isolate the effect. In Europe, governments' efforts to limit end-user price variations, alongside with limited panel size, blur the message. Although results have there to be taken with caution for methodological and theoretical reasons, the overall results still suggest that CRM implementation could be financially neutral for end-users. Altogether, this supports previous results: CRMs might not be so costly. Regulators interventions seem to limit the cost of CRM, so that it does not exceed the reduction in scarcity rent³⁹.

³⁹If there is a reduction in missing money thanks to CRM implementation (lower risk), it suggests that even though reliability is not valued in the energy market, producers do benefit of alternative revenues so the reserve margin in all the states of our panel is not at risk.

Finally, this study presents one of the first attempt to empirically estimate the average cost of CRM for end-users. The cost of precaution could not be set forward. Mostly, the conditional effect is insignificant except in the US where the coefficient is negative. This is a strong result that suggests that the risk reduction has been underestimated in a debate where CRMs are naturally seen as costly, or at best neutral and unneeded. Neutral and unneeded; it may be, but costly, probably not. Giving ground to its defenders, CRMs should not be seen solely as a precaution: a precaution that comes for free deserves attention. However, this analysis also provides arguments for CRMs detractors. Indeed, the US states in the panel are the only ones with a significant and negative coefficient. They are also more homogeneous systems in the sense that they all implemented designs with CRMs around the same period, following deregulation. In this sense, this gives little insight into the relative efficiency of a market design with CRM and without (EOM). In any case, it should raise regulators' awareness regarding the cost efficiency of CRMs. It is also the regulator's choice to improve the quality and detail of published data so researchers can investigate potential improvements in the security of supply or system costs. Unfortunately, data availability does not allow differentiating between network failures and capacity inadequacy for now, nor to investigate at a more granular level.

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Appendices

Appendix K

Database

K.1 Data sources

European electricity price to the industrial end-user: The original eurostats series "Ie" (1991-2007) and then "IC" (2007-2015), representing medium size firms with an average consumption of 2000MWh/year approximatively. Data are taken excluding VAT and other recoverable taxes and levies. Eurostats industrial data may include any non-domestic consumer depending on country coverage.

European electricity price to the residential end-user (household): The original eurostats series "DC"(2007-2015), representing middle range households with an average consumption of 3500kWh/year approximatively. Data are taken excluding VAT and other recoverable taxes and levies for consistency with industrial end-user prices.

European gas prices to the industrial end-user: The eurostats serie "I3-I" (1997-2007) and then "I3", representing medium size firms with an average of 50000GJ/Year approximatively. Data are taken excluding VAT and other recoverable taxes and levies.

European electricity fuel mix: The International Energy Agency publishes the electricity production by fuel by country which divided by the total production gives a percentage. Hydroelectric and nuclear production are straight forward and respectively correspond to the items "hydro" and "Nuclear". The productions from "solar", "solar photovoltaic", "solar thermal" and "wind" are considered as renewable. According to the IEA report, the category "coal" gathers "Other bituminous coal", "Sub-bituminous coal", "LigniteBKB/peat briquettes", "Blast furnace gas", "Anthracite", "Coke oven gas", "BitumenPetroleum coke", "Coke oven coke", "Coal tar", "Peat", "Coking coal", "Patent fuel", Peat products".

US industrial electricity price: The EIA publishes directly the yearly average industrial power prices for each state for the 1990-2014 period.

US residential electricity price: The EIA publishes directly the yearly average Residential power prices for each state for the 1990-2014 period.

US industrial gas price: The EIA publishes directly the yearly industrial gas prices for each state for the 1997-2014 period. To extend the series and complete missing values, the wellhead prices variation are used.

US electricity fuel mix: The EIA openly publishes production by fuel for each state. Hydroelectric production gathers conventional "hydro" and "pumped storage" while renewable production is composed of "solar thermal" and "photovoltaic" as well as "wind". Coal and gas and nuclear items are used as such. Productions by fuel are then divided by total production to get a share.

K.2 Capacity remuneration in our panel

| State | System | Current CRM | Short term | Forward |
|-------|----------------|-------------|------------|---------|
| FR | France | - | - | 2017 |
| BE | Belgium | - | - | - |
| DE | Germany | - | - | - |
| UK | United Kingdom | Short Term | Until 2001 | 2018 |
| IE | Ireland | Short Term | 2007 | 2017 |
| ES | Spain | Short Term | 1997 | - |
| PT | Portugal | Short Term | 2010 | - |
| IT | Italy | Short Term | 2004 | 2017 |
| CT | ISO-NE | Forward | 1998 | 2010 |
| MA | ISO-NE | Forward | 1998 | 2010 |
| ME | ISO-NE | Forward | 1998 | 2010 |
| NH | ISO-NE | Forward | 1998 | 2010 |
| RI | ISO-NE | Forward | 1998 | 2010 |
| VT | ISO-NE | Forward | 1998 | 2010 |
| NY | NYISO | Short Term | 1999 | - |
| KY | PJM | Forward | 1999 | 2008 |
| NJ | PJM | Forward | 1999 | 2008 |
| OH | PJM | Forward | 1999 | 2008 |
| PA | PJM | Forward | 1999 | 2008 |
| VA | PJM | Forward | 1999 | 2008 |
| WV | PJM | Forward | 1999 | 2008 |
| KS | SPP | - | - | - |
| NE | SPP | - | - | - |
| OK | SPP | - | - | - |
| TX | ERCOT | - | - | - |

Table K.1: CRMs description

The load duration curve of **France** is quite steep and by 2012, the SO started to bother about investments trends due to the mothballing of several plants. Forward capacity obligations is implemented with a first delivery year in 2017.

In the fear of aging nuclear plants, **Belgium** has decided to keep the EOM going by implementing a strategic reserve in 2014. The strategic reserve is not supposed to be price distortive when well managed. **Germany** has temporarily considered capacity remuneration, but finally decided to implement a targeted strategic reserve with the double aim to take old polluting plants out of the market, but keep them into a reserve in order not to lower security of supply.

The United Kingdom implemented capacity payments from 1990 to 2001. The capacity payments were calculated ex post based on the realized scarcity in market for 30 minutes slots. In 2013, National Grid decided to implement a capacity market from delivery years 2017 on.

In **Ireland**, since 2007, the total sum of capacity payment is calculated by the market operator as the product of the targeted quantity with the estimated missing money of a new peaker (fixed costs minus the infra marginal rent and the ancillary services revenues. This sum is then charged allocated to generators according to three principles. 30% is paid every month as a fixed payment. Ex post payments also represent a 30% of the annual capacity payment sum based on the ex post loss of load probability in each trading period and finally, a 40% of the sum is allocated according to the forecasted LOLP in each trading period of the month.

Spain has had capacity payments since 1997. Prices were then set by the government according to expected adequacy needs and would differ depending on fuel. In 2007, the system was reformed to become more targeted. Only new built or existing plants not recovering fixed costs would then possibly receive a capacity payment.

In 2007, **Portugal** decided to follows Spain with the new capacity payment.

Following the 2003 blackout, **Italy** implemented a temporary mechanism. Allocated on a daily basis, the payment has two components. One is based on the forecasted hourly supply and demand, the second one depends on realized day ahead prices.

ISO New England first implemented a capacity market as soon as 1998. In 2006, it decided to change for a forward capacity market and set a transition period of 3 years (2007-2010) during which capacity payments would bridge in between the two mechanisms. As of auctions from delivery year 2010/2011, the forward period has been 3 years with one year commitment.

Although **NYISO** has changed its mechanism in place since 1999 to a forward capacity mechanism in 2006, it kept its short term feature with a forward period of only one month. This paper considers a forward period to be implemented when it is of at least one year.

The **PJM** decided in 1999 for a daily capacity market where utilities would buy and sell capacity to comply with their obligation. In 2007, it has been reformed to become a forward capacity market with a 3 year forward period. 2007-2011 has been a transition period with increasing forward period from delivery year to delivery year. 2008 is the first delivery year benefiting from several months of forward period.

SPP and **ERCOT** have not implemented any capacity mechanism so far. Contrary to the other systems considered, SPP does not have an independent system operator. We also act as if the whole state of Texas was in the ERCOT which is only a proxy, several counties being actually in the SPP.

Appendix L

Descriptive statistics figures and tables

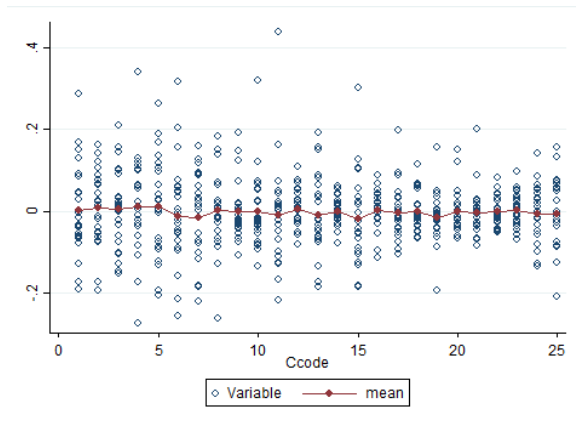


Figure L.1: Real industrial power prices per state (Ccode)

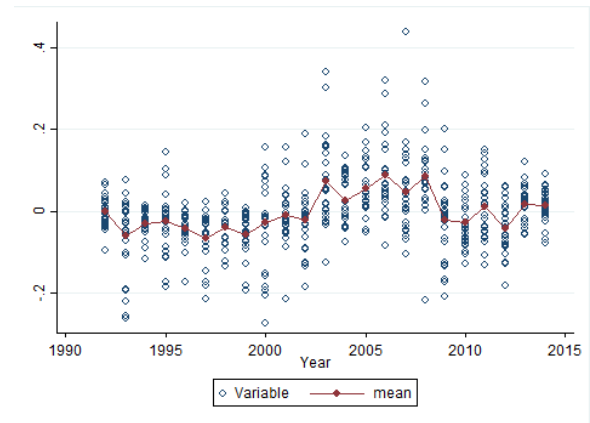


Figure L.2: Evolution of first differenced real industrial power prices over time

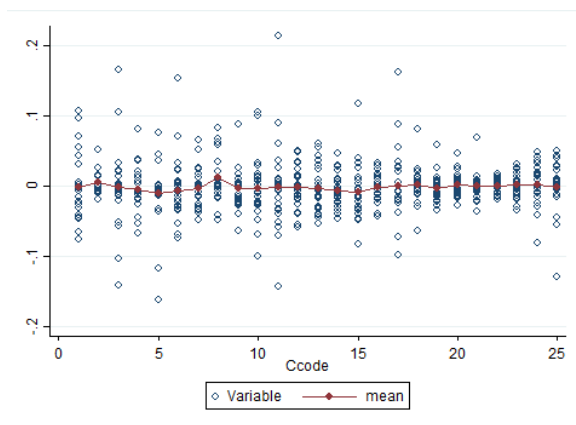


Figure L.3: Ratio industrial over residential prices per state

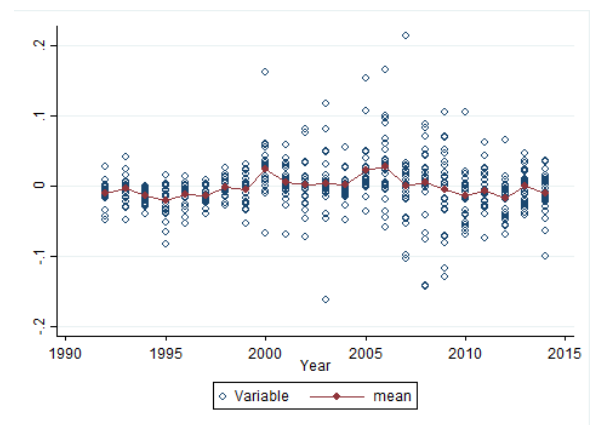


Figure L.4: First differenced ratio industrial over residential prices over time

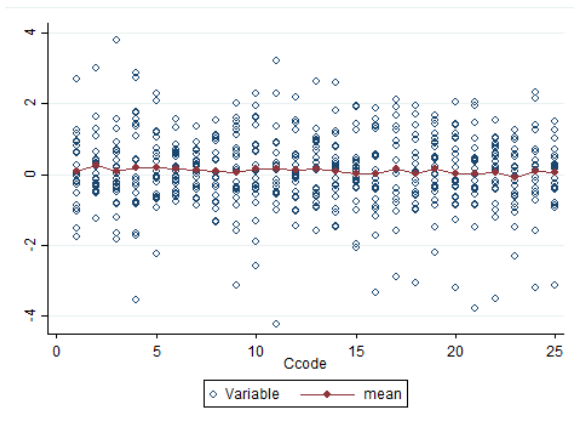


Figure L.5: Real industrial gas prices per state

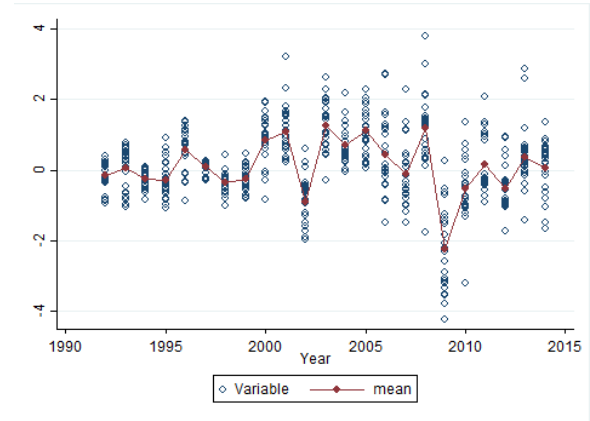


Figure L.6: Evolution of first differenced real industrial gas prices over time

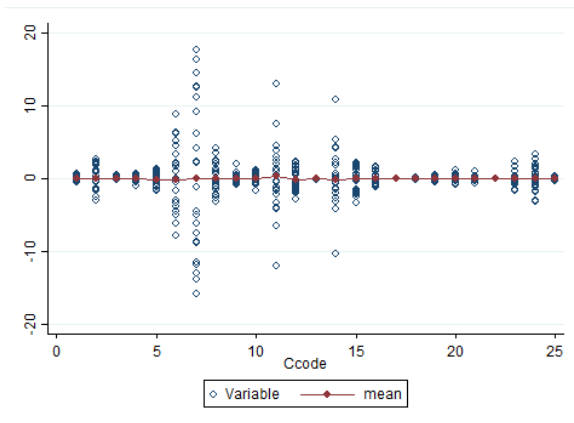


Figure L.7: Hydroelectric share in total power production per state

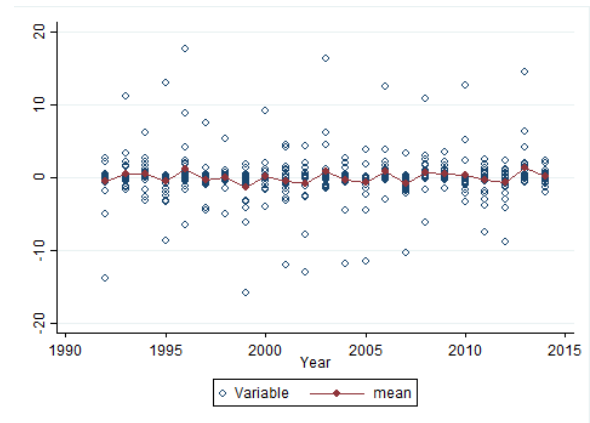


Figure L.8: Evolution of the first differenced hydroelectric share of total power production over time

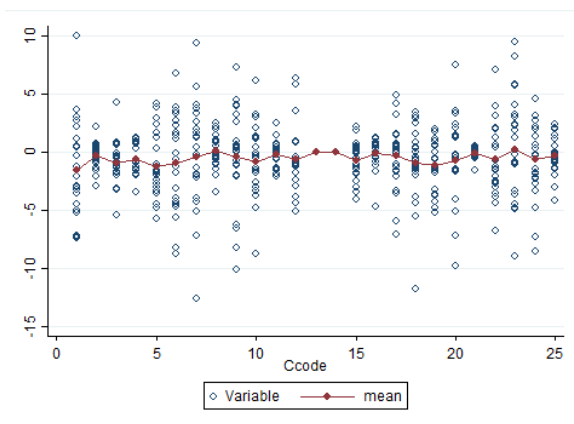


Figure L.9: Share of power production from coal per state

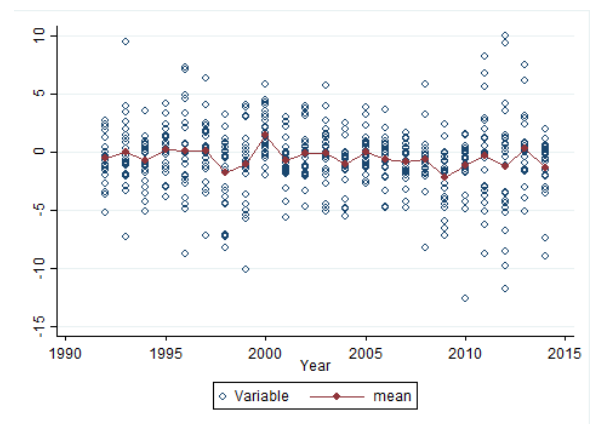


Figure L.10: Evolution of first differenced share of coal fired power production over time

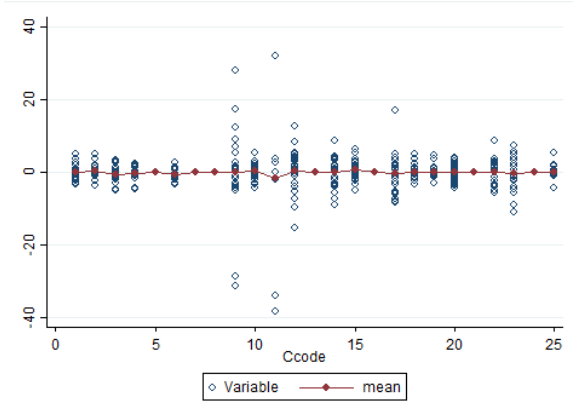


Figure L.11: Share of power production from nuclear per State

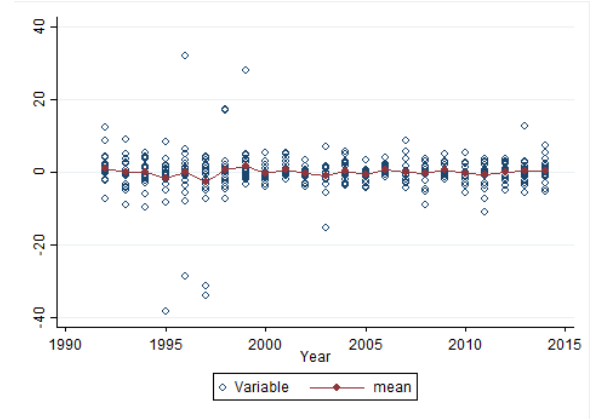


Figure L.12: Evolution of the first differenced share of nuclear power production over time

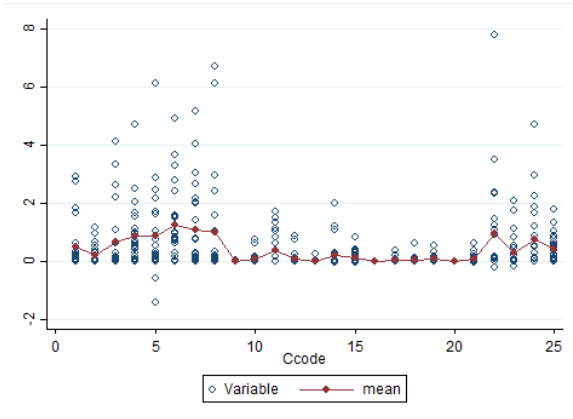


Figure L.13: Share of power production from Renewable sources per state

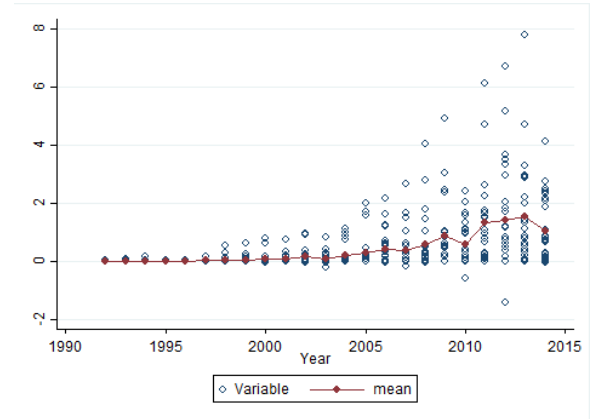


Figure L.14: Evolution of the first differenced share of renewable power production over time

| Variables | All | All | CRM | CRM | EOM | EOM | CRM-EOM | CRM-EOM |
|----------------------------|-------|-------|-------|-------|-------|-------|-----------------|----------------|
| | Mean | SD | | | | | Mean difference | SD difference |
| <i>Price</i> | 61.91 | 24.03 | 63.02 | 22.72 | 56.11 | 28.22 | different | different |
| $\ln(\text{Price})$ | 4.05 | 0.39 | 4.08 | 0.38 | 3.96 | 0.44 | different | different |
| <i>Price_{Res}</i> | 96.35 | 33.20 | 96.79 | 30.29 | 94.85 | 43.53 | similar | different |
| $\ln(\text{Price}_{Res})$ | 4.77 | 0.38 | 4.52 | 0.31 | 4.46 | 0.40 | different | different |
| <i>PriceRatio</i> | 0.63 | 0.10 | 0.64 | 0.11 | 0.60 | 0.06 | different | different |
| <i>GasPriceReal</i> | 4.51 | 0.33 | 5.36 | 2.14 | 5.32 | 2.65 | similar | different |
| <i>HydroProd</i> | 6.99 | 8.41 | 8.19 | 9.30 | 3.88 | 4.12 | different | different |
| <i>ResProd</i> | 1.89 | 4.58 | 1.63 | 4.59 | 2.57 | 4.49 | similar | similar |
| <i>NukeProd</i> | 24.50 | 23.48 | 22.01 | 22.47 | 30.89 | 24.86 | different | similar |
| <i>CoalProd</i> | 35.95 | 29.02 | 33.35 | 30.56 | 42.61 | 23.42 | different | different |
| number of observations | 600 | | 168 | | 432 | | | |

Table L.1: Differences in mean and standard deviation between two groups of states (5% sign level)

| Variables | All Mean | All SD | CRM Mean | CRM SD | EOM Mean | EOM SD | CRM-EOM Mean diff. (t-test) | CRM-EOM SD diff. (t-test) |
|----------------------------------|-------------|-----------|-------------|-----------|-------------|-----------|-----------------------------------|---------------------------------|
| $\Delta \ln(\text{Price})$ | -0.0022 | 0.0862 | -0.0039 | 0.0876 | 0.0022 | 0.0828 | similar | similar |
| $\Delta \ln(\text{Price}_{Res})$ | 0.0005 | 0.0703 | -0.0001 | 0.0707 | 0.0025 | 0.0695 | similar | similar |
| $\Delta \text{PriceRatio}$ | -0.0017 | 0.0358 | -0.0024 | 0.0370 | -0.0001 | 0.0325 | similar | similar |
| $\Delta \text{GasPriceReal}$ | 33.4900 | 29.4098 | 33.0145 | 25.93 | 34.7127 | 36.9413 | similar | different |
| $\Delta \text{HydroProd}$ | -0.0225 | 2.7413 | -0.0205 | 3.1798 | -0.0278 | 0.9271 | similar | different |
| $\Delta \text{ResProd}$ | 0.3969 | 0.9476 | 0.3211 | 0.8810 | 0.5919 | 1.0793 | different | different |
| $\Delta \text{NukeProd}$ | -0.1284 | 4.3137 | -0.1109 | 4.8153 | -0.1732 | 2.6268 | similar | different |
| $\Delta \text{CoalProd}$ | -0.5485 | 2.7720 | -0.5793 | 2.7980 | -0.4693 | 2.7111 | similar | similar |
| Number of obs. | 575 | | 414 | | 161 | | | |

Table L.2: Differences in mean and standard deviation between two groups of states (5% sign level)

Appendix M

Robustness

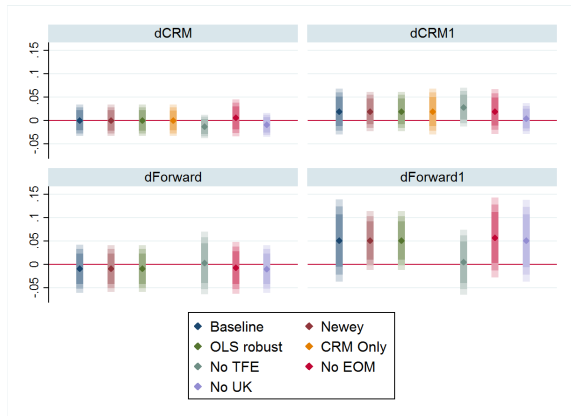


Figure M.1: Industrial power prices (Pooled panel):
CRM & Forward coefficients (confidence interval 95, 90 & 80%)

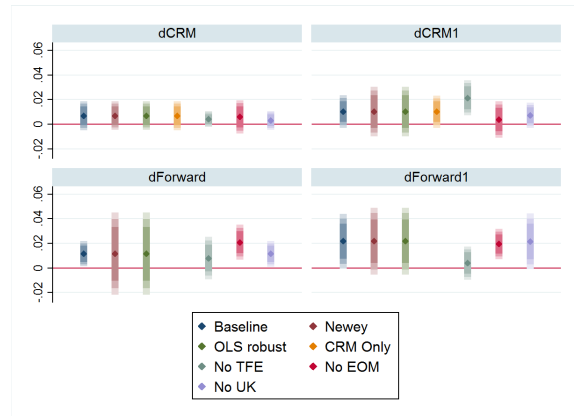


Figure M.2: Ratio industrial over residential power prices (Pooled panel): CRM & Forward coefficients (confidence interval 95, 90 & 80%)

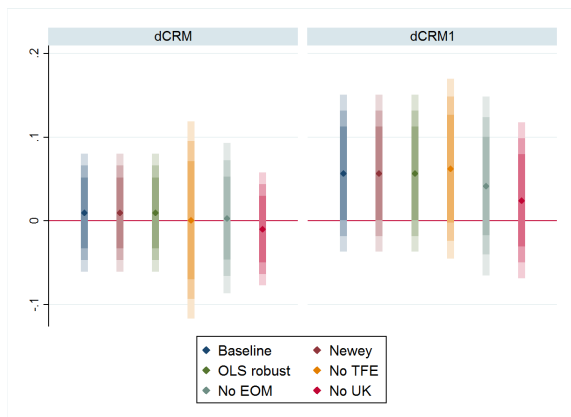


Figure M.3: Industrial power prices (EU):
CRM & Forward coefficients (confidence interval 95, 90 & 80%)

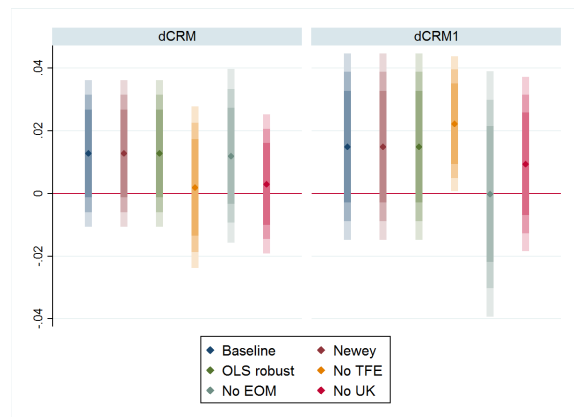


Figure M.4: Ratio industrial over residential power prices (EU): CRM & Forward coefficients (SE 95, 90 & 80%)

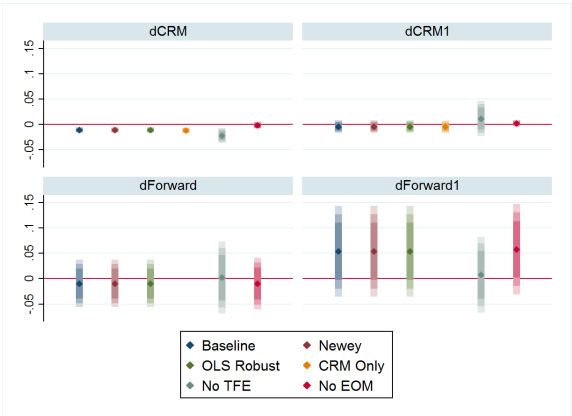


Figure M.5: Industrial power prices (US): CRM & Forward coefficients (confidence interval 95, 90 & 80%)

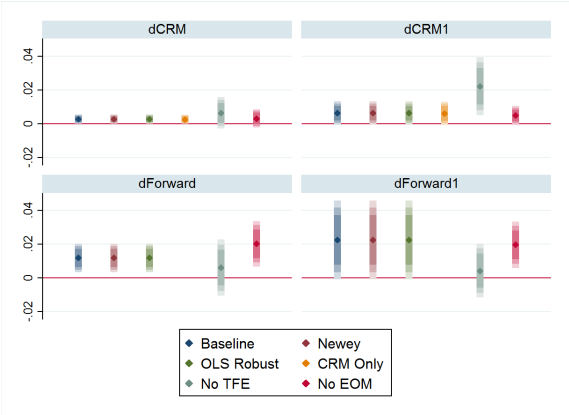


Figure M.6: Ratio industrial over residential power prices (US): CRM & Forward coefficients (confidence interval 95, 90 & 80%)

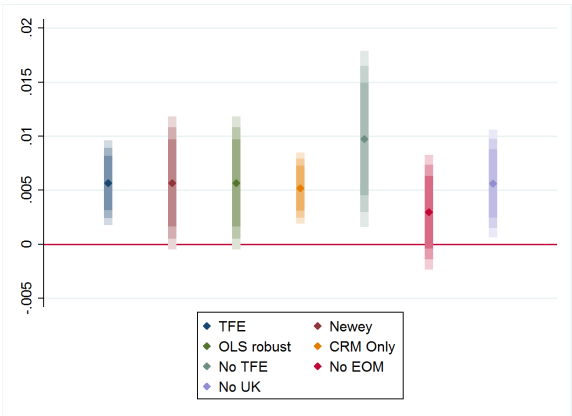


Figure M.7: Industrial power prices (Pooled panel): Renewable production coefficients (confidence interval 95, 90 & 80%)

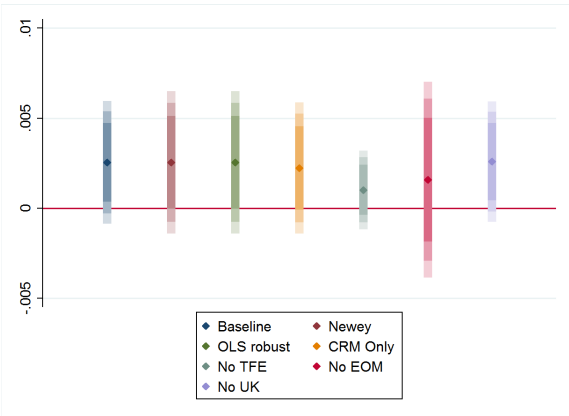


Figure M.8: Ratio industrial over residential power prices (Pooled panel): Renewable production coefficients (confidence interval 95, 90 & 80%)

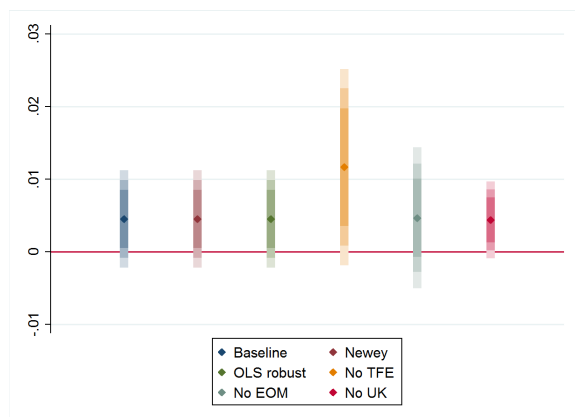


Figure M.9: Industrial power prices (EU): Renewable production coefficients (confidence interval 95, 90 & 80%)

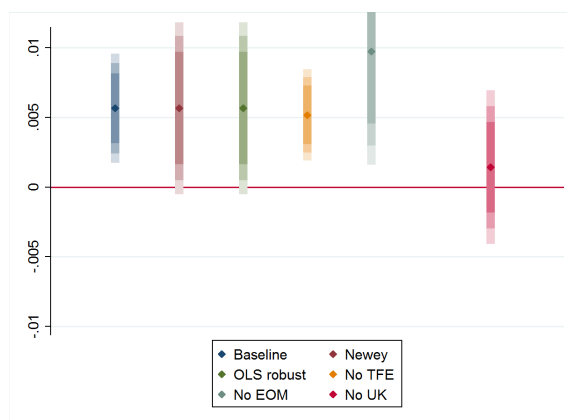


Figure M.10: Ratio industrial over residential power prices (EU): Renewable production coefficients (confidence interval 95, 90 & 80%)

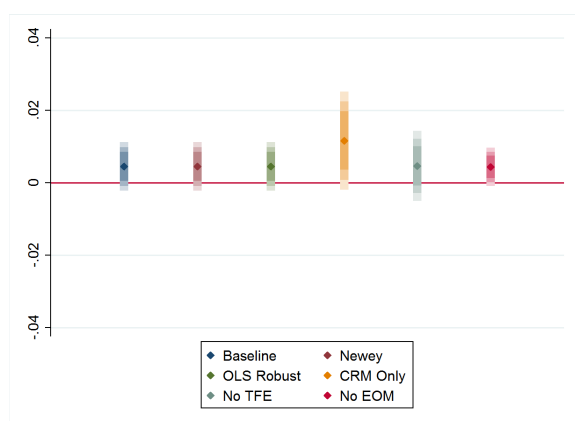


Figure M.11: Industrial power prices (US): Renewable production coefficients (confidence interval 95, 90 & 80%)

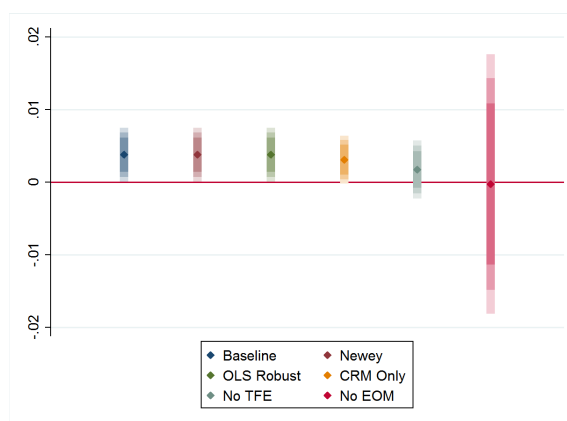


Figure M.12: Ratio industrial over residential power prices (US): Renewable production coefficients (confidence interval 95, 90 & 80%)

| VARIABLES | (1) Model 1 Pooled $\Delta \ln(Price_{Res})$ | (2) Model 2 Pooled $\Delta \ln(Price_{Res})$ | (3) Model 2 EU $\Delta \ln(Price_{Res})$ | (4) Model 1 US $\Delta \ln(Price_{Res})$ | (5) Model 2 US $\Delta \ln(Price_{Res})$ |
|-----------------------------------|---|---|---|---|---|
| ΔCRM | -0.00964 (0.00867) | -0.00972 (0.00861) | -0.00688 (0.0169) | -0.0161*** (0.00216) | -0.0162*** (0.00211) |
| $\Delta CRM1$ | 0.00262 (0.0154) | 0.00263 (0.0154) | 0.0315 (0.0245) | -0.0142*** (0.00125) | -0.0142*** (0.00122) |
| $\Delta Forward$ | -0.0229 (0.0177) | | | -0.0239 (0.0162) | |
| $\Delta Forward1$ | 0.0104 (0.0261) | | | 0.0121 (0.0256) | |
| $\Delta GasPriceReal$ | 6.08e-05 (0.000152) | 5.63e-05 (0.000159) | 0.000119 (0.000104) | 1.32e-05 (0.000271) | 3.66e-06 (0.000286) |
| $\Delta HydroProd$ | -0.000436 (0.000548) | -0.000370 (0.000568) | 0.000178 (0.000621) | -0.00181 (0.00111) | -0.00152 (0.00109) |
| $\Delta ResProd$ | 0.00173 (0.00237) | 0.00177 (0.00214) | 0.00221 (0.00450) | 0.00171 (0.00100) | 0.00180 (0.00117) |
| $\Delta NukeProd$ | -0.000319 (0.000341) | -0.000345 (0.000349) | -0.000685 (0.00245) | -0.000430 (0.000317) | -0.000431 (0.000336) |
| $\Delta CoalProd$ | -0.000851 (0.000764) | -0.000867 (0.000853) | -0.00109 (0.00178) | -0.000650 (0.000562) | -0.000687 (0.000647) |
| Constant | 0.0141*** (0.00258) | 0.0142*** (0.00276) | 0.0348*** (0.00329) | 0.00525 (0.00339) | 0.00531 (0.00352) |
| Regional Time fixed effects | YES | YES | YES | YES | YES |
| Observations | 575 | 575 | 184 | 391 | 391 |
| R-squared | 0.600 | 0.598 | 0.771 | 0.238 | 0.232 |
| Number of groups | 25 | 25 | 8 | 17 | 17 |

Standard errors in parentheses
 *** p<0.01, ** p<0.05, * p<0.1

Table M.1: Residential power prices: Regression results – Robustness checks

Conclusion

1 An original research question

Market imperfections generate reasonable doubt on the ability of energy-only markets (EOMs) to provide socially optimal levels of capacity on their own [Cramton et al., 2013]. However, reasonable doubt also exists regarding the efficiency of market interventions. The difficulty in quantifying the inefficiencies on the electricity market [Bublitz et al., 2019] makes both empirical research and decisions in terms of market design difficult. This is especially true regarding the adequacy problem. Indeed, adequacy is not a direct outcome of the market since investment incentives result from the expected price and quantities and not the actual equilibrium. From investment decisions ensue the probability of capacity-related outages (i.e. when capacity is unable to supply to demand in its entirety). In addition, whatever the causes, outages have similar costly consequences, as illustrated by the recent black-out in London (August 9th, 2019)¹ that affected everything from businesses, traffic lights and trains to hospitals, recalling in the starkest of manners the high private and social costs of involuntary and unanticipated interruptions of electricity supply. The absence of functioning information screens and mobile networks made mitigation efforts difficult while Ipswich Hospital additionally faced the failure of its own back-up generator². This is why limiting the occurrence of outages is often seen as a public objective.

The assessment of the different market designs in terms of adequacy is all the more complex as adequacy deals with extreme and rare events, meaning that improvements in terms of security of supply (SoS) are only tangible on limited occasions. Along with the associated externalities [Keppler, 2017], this explains why such broad ranges of value of lost load (VoLL) coexist [Royal Academy of Engineering, 2014]. Adequacy thus becomes a key market design issue for two concomitant reasons. The first one is the difficult assessment of inefficiencies in electricity markets. The second is the lack of responsiveness from consumers, which favors protective behavior from the public authority. In this context, the decision to implement CRMs can mainly be seen as a precaution: even without a precise estimation of the inefficiencies generated by potential market imperfections, the social and private costs of outages are considered so high that forcing a given reliability

¹See <https://www.bbc.com/news/uk-49302996> accessed on August 10th, 2019.

²See <https://www.bbc.com/news/uk-england-suffolk-49299837> accessed on August 10th, 2019.

target appears as the most suitable option to avoid those.

There exists a wide variety of CRMs that aim towards securing a given level of SoS. With the exception of chapter 2, this doctoral thesis has focused on the most common CRMs, leaving aside reserves. This choice is motivated by the structural differences in investment incentives that are expected to lead to distinct market dynamics. Indeed, capacity payments (CP), capacity markets (CM) and reliability options (RO) provide a separate revenue from the energy market which is expected, at least partially, to replace the scarcity rent. On the contrary, reserves seek to improve investment incentives by restoring efficient scarcity rent. They fall out of the scope of this analysis not because they represent a less interesting or efficient tool to ensure SoS, but because one needs to set limits to the research question.

Similarly, instead of questioning the choice of CRM implementation, this study seeks to understand what happens once the decision to intervene through the implementation of a CRM is made. As a first step, the CRM needs to be tailored, which, given the amount of possible features (chapter 1) is far from an easy task. The second step is understanding the consequences of such a decision through a performance assessment. Each of them is tackled in two chapters, using a combination of methods from empirical case studies to a Cournot model via literature analysis and econometrics.

The variety of possible market design, as well as the existence of heterogeneity between the systems, tend to untie the causes –design features– from the effects –performance–. This is true for all alternative market designs, be it EOM, CRM, or any other. While heterogeneity between the systems tends to shift the focus at the system level, the first chapter considers the individual evolution of CRM regulation in different systems to understand the global evolution of knowledge and beliefs. Amongst the identified channels of learning are the stakeholders and more specifically, the market actors. Indeed, they have private information that the public authority cannot uncover by herself. chapter 3 thus investigates actors’ preferences in terms of capacity requirements when the capacity market is decentralized, and the number of LSEs is limited. With respect to performance assessment, chapter 2 builds on the existing modeling literature to derive robust conclusions on CRM performance compared to the EOM. Indeed, a conclusion concerning SoS, consumer surplus, investment cycles, or price volatility that holds under different specifications, with different models, is likely to hold in heterogeneous systems as well. Complementarily, a precaution is only worth taking if its net cost is limited –compared to the expected benefits–. This is the purpose of the last chapter, which considers the conditional average effect of CRM implementation on end-user prices.

The following section presents the main findings of this doctoral thesis first with respect to performance assessment and then to CRM regulation-making. As discussed earlier, those questions remain unsettled, mainly because of the complexity of real-life dynamics. Naturally, this limit also applies to the present results which modestly contribute to the discussion.

2 Main findings

2.1 Performance assessment

The most self-evident finding of the study is the absence of a general consensus on the valuation of the consumer surplus (chapter 2). Existing discussions on the VoLL, both in terms of definition³ or value –it can vary by consumer group, outage duration or notice delay– highlight the difficulty of the task. By extension, this also applies to welfare estimation. According to chapter 2 this lack of agreed on valuation of surpluses is limiting the policy recommendations made in the literature. Indeed, while authors tend to conclude that CRMs do improve SoS, reduce price volatility and the amplitude of investment cycles, they cannot agree on the effect on the consumer surplus. Some studies find end-user prices to decrease under CRMs [Höschle et al., 2017; de Vries and Heijnen, 2008]: along with an increase in SoS, the effect on surplus is positive. However, when end-user prices increase with CRMs [Iychettira et al., 2014], the valuation of avoided outages dramatically affects the resulting consumer surplus. This limit drives some authors to renounce the valuation of the consumer surplus, only providing raw data on outage rates and prices.

Indeed, although efforts are made to uncover the VoLL for different categories of consumers [Royal Academy of Engineering, 2014]⁴, it remains a private value and as such might underestimate the actual value of SoS. This is why CRMs are implemented as a precaution, to safeguard consumers against the adverse effects of outages. However, a precaution is only worth taking if the cost does not outweigh the expected benefits. While the benefits depend on how the outages are valued, chapter 2 has also highlighted divergences in the conclusions with respect to the net cost. Indeed, the additional capacity component inflates the total system costs, but the increased available capacity should also lead to lower average electricity prices by way of reducing the scarcity rent. Empirically contributing to the discussion, chapter 4 considers yearly end-user power prices as the mirror of average system costs. When controlling for system characteristics, the absence of a statistically significant effect suggests a high heterogeneity of effect, mainly due to the significant differences in design. This intuition gains ground when considering Europe and the US states separately. Indeed, the standard deviation shrinks in the American sub-panel –where the CRMs implemented were much more similar– to suggest that CRMs are rather related, on average, with a small decrease in industrial end-user prices. When investigating how residential end-user power prices evolve against industrial ones, results imply a reduction of the gap between the two. The residential end-users would benefit more from CRM implementation than their counterparts. Considering the complex dynamics embedded in end-user prices, the causality is disregarded. Yet, this contributes to the literature for being the first attempt to empirically quantify the average net cost of a CRM.

³For instance, according to the European Union Electricity Market Glossary, the VoLL is "The value attributed by consumers to unsupplied energy" while Cramton et al. [2013] considers that it is the average value placed by end consumers on losing power in an average rolling black-out.

⁴See also the presentation from Cambridge Economic Policy Associates 2018 accessed on August 12th, 2019.

2.2 Regulatory process

Both chapter 2 and chapter 4 suggest a crucial role of CRM design in performance. With this respect, the analysis of past and existing CRM designs highlights not only the diversity of possible designs but also a form of simultaneity in the timing of re-design. More importantly, this is done along with similarities in the lessons drawn and the improvements made (chapter 1). For instance, the first wave of CRMs –the 90s– was commonly plagued with price volatility and strategic behavior. As a consequence, most systems improved the assessment of firm capacity and increased the obligations associated with the capacity remuneration as well as the contract duration. This also applies to the newly implemented CRMs such as Italy, Ireland, or MISO despite their heterogeneity, suggesting a form of cross-system learning .

This naturally questions on what basis does the regulator decide the design to be implemented. Whereas the regulatory challenge consists in identifying and implementing the most efficient design, both the literature and the results presented above indicate that what should be a local process is actually fueled by international experiences as well. This interaction between the local and global levels can be analyzed in terms of social learning. The first step to understand the learning process is to identify which elements of the design are most affected by heterogeneity –e.g. by exogenous factors and motives–. Those will remain in the local scope and should be mostly unaffected by what happens at the international level. On the contrary, the design features that do converge are those to which foreign experience has been deemed relevant. Reasoning in this framework not only identifies and characterizes design features but also sets out the cross-system learning dynamics (chapter 1). The learning channels, as well as the pace of adoption of the converging features, are also highlighted. Indeed, the implemented CRM designs are getting more and more market based with a tendency towards centralization –with the notable exception of France, which is further discussed in chapter 3–. Increased attention is paid to the obligations of the supply-side and to product definition as a whole. This includes related penalties. Contract duration is generally increased, and the demand made elastic to stabilize the market. Apart from the apparent system-specific features such as the critical period indicator, the reliability criterion or the locational component, the elements related to new technologies also fail to converge. It is indeed surprising that given design features would converge for conventional technologies, but not for their alternative. In this sense, the technological progress is analyzed as an exogenous shock disrupting the learning process: some converging features become questioned for not suiting the broader range of available technologies better.

As chapter 1 takes a holistic view to understand how suitable CRM features are identified, the local learning process remains in the shadow of the international one. The main difference with the latter lies in public consultations where stakeholders are invited to express their views about regulatory changes. Chapter 3 precisely investigates market actors' preferences. In a Cournot Oligopsony, this chapter questions the dynamics leading

to a decentralized capacity market with *ex post* requirements, and more precisely, the actors' preferences. As discussed, the recently implemented French CRM operates in this framework while most contemporaneous designs function in a centralized way. In this sense, such a choice does not emanate from cross-system learning. Modeling *ex post* requirements as uncertainty on the future level of demand, they are never found to maximize capacity buyers (mainly load-serving entities) and capacity owners' surpluses at the same time. If the buyer-side is imperfectly competitive, they can, however, be welfare-maximizing when the supply curve is increasing quickly, and the opportunity cost of not buying enough capacity is low. This means that either the penalty is set too low or that capacity buyers can shed their load at limited costs, thus avoiding any penalty. On the contrary, *ex ante* requirements will always maximize the welfare under perfect competition. Whatever the level of competition, actors might agree towards *ex ante* requirements. Results also show that the preferences emerging from the heterogeneous capacity owners might not reflect the profit-maximizing design. Although this situation is commonly accounted for by the public authority, model calibrations highlight the limited risk of such an issue. In this sense, the public authority can effectively use the response to public consultations to derive the surplus and profit-maximizing designs –as long as the actors do reveal their true preferences–.

3 Limits, practical implications, and recommendations for further research

In terms of performance assessment, this study has encountered the same obstacle as most contemporaneous authors: the valuation of SoS. This topic is being increasingly tackled each year with studies estimating the VoLL each time at a more granular level or even directly empowering consumers via real-time pricing. Until consensus is reached on the –private and social– value of SoS, CRMs will never be fully legitimate –or illegitimate for that matter– and remain a precaution. This study has highlighted the efforts made to improve the performance of CRMs over time. However, this does not mean that CRMs have started to outperform the EOM because energy, ancillary, and balancing markets have been enhanced as well over the period. Yet, this study contributes to the existing literature by, on the one hand, synthesizing the results from modeling papers to set out the current state of knowledge and, on the other hand, providing the first empirical assessment of the net cost of CRM implementation. This last point is precisely the main unsettled aspect according to the modeling literature.

Each in their own way, chapters 1, 2, and 4 suggest that the private cost is rather limited: precaution might be worth taking considering the possible social implications. Indeed, the evolution of CRMs over time has shown that it is a rare event to have a public authority renounce capacity remuneration to go back to the EOM, suggesting that the public authority finds its way around. The fact that it effectively improves SoS and reduces price volatility is probably a good reason for that. Most importantly, results suggest that

CRMs might have a limited (possibly negative) financial impact on consumers, meaning that it would be worth taking the chance of implementing a CRM. However, most standard errors in chapter 4 indicate that the evolution of end-user prices has a 95% probability of being between $\pm 5\%$ on average. While this mainly comprises acceptable costs, the upper value is much higher than any estimate of the VoLL. As such, the analysis does not firmly conclude on the acceptability of CRMs as a precaution. Again, these results with respect to CRM performance only indicate why CRM implementation might be a rational decision given the current state of knowledge. They do not justify the intervention for not assessing the actual need for such a thing.

By mainly reasoning at the aggregate level, the study partially abstracts from local specifics which, as discussed in chapter 1 are a necessary filter in choosing a design. One could argue that such a filter is slowly becoming irrelevant if designs are actually converging. However, past experiences are imperfectly informative in a dynamic context. This is one of the take away from chapter 3: a reason to favor *ex post* requirements could be the existence of cheap untapped demand response (low opportunity cost of under-procurement). Unleashing this potential is subject to the diffusion and exploitation of new technologies.

Ultimately, the reach of this analysis as a whole is limited by its scope itself. Indeed, the focus is set on CRMs and their interrelation with the energy market. This does not only disregard alternative sources of revenues for generators and investors but it also ignores potential strategic behaviors on the supply-side. The importance of such considerations is mentioned in chapters 1, 2, and 3 but never actually tackled until chapter 4, which does so implicitly. Indeed, focusing on end-user prices allows accounting for all possible interactions between the markets and strategies of the market players. Doing so in a pool of countries with distinct market designs implies renouncing the ability to disentangle the causes from the effects. Although identifying such causality would certainly have been desirable, its feasibility can be reasonably doubted given the lack of sufficiently granular data available over sufficiently long timeframes.

Having analysed the capabilities of CRMs to improve welfare from a number of different angles and with different methodologies, this doctoral thesis in economics has addressed an important gap in the literature and identified a number of relevant results. Nevertheless, these the final judgement on the performance of CRMs remains in suspense. On the one hand, there are a number of indicators that CRMs do indeed improve security on supply at overall limited costs and thus improve welfare. On the other, the complexity of real-life situations in which CRMs operate encourage caution when generalizing both from experience and theoretical results. The four chapters try to bridge it both ways, combining different methods. However, a lot remains to be investigated. One direction for future research is to focus on the different time horizons of the SoS. As discussed in chapter 1, but also suggested in chapter 3, new technologies come as a disruption to the convergence process. This is because they come as a disruption for the whole sector.

The new SoS challenges are not only moving the issue towards the short term; they also involve different types of complementary contributions to SoS. This further increases the complementarity between the different electricity products and might force public authorities to rethink the market: new products are needed to tackle decarbonization, digitalization, and decentralization at the same time. This will fundamentally restructure regulation-making as we know it by increasing the role of different actors in the process.

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RÉSUMÉ

Les mécanismes de capacité (CRM) sont instaurés pour aligner l'équilibre de marché avec l'optimum social, c'est-à-dire assurer la sécurité d'approvisionnement au moindre coût. Sur le plan théorique, les marchés energy-only sont censés atteindre cet objectif, mais leur efficacité est mise en doute. Si le bien-fondé de la qualification des CRMs comme mécanisme optimal de second rang occupe les chercheurs depuis plusieurs décennies, l'évaluation empirique des CRMs a reçu une attention beaucoup plus limitée. Cette lacune constitue un domaine de recherche académique fertile, mais limite la capacité de chacun à transposer les résultats théoriques en termes d'élaboration de politiques publiques. L'évaluation empirique des CRMs est d'autant plus nécessaire que leur performance dépend non seulement de paramètres structurels, techniques et culturels spécifiques à chaque pays, mais aussi des détails de leur mise en oeuvre. A ce titre, cette thèse présente le premier travail traitant de la performance empirique des CRMs ainsi que des choix de mise en oeuvre réglementaire. L'étude de la convergence relative des designs des CRMs depuis les années 90 permet l'identification des caractéristiques indispensables à leur succès quand les divergences de résultats dans la littérature quantitative existante aident à prendre la mesure des défis futurs restants. Le coût net d'une telle intervention sur le marché est aussi discuté à l'aide d'une approche économétrique trans-nationale. Enfin, les préférences des agents quant à la précision de l'information sur les obligations de capacité sont abordées dans un modèle analytique.

MOTS CLÉS

Marché d'électricité, Mécanismes de capacité, Sécurité d'approvisionnement, Précision de l'information, Réglementation

ABSTRACT

Capacity remuneration mechanisms (CRMs) are widely implemented as an attempt of correcting the real-world imperfections of electricity markets and aligning market outcomes with social optimality. Mainly, many observers doubt the ability of the EOM to provide sufficient investment incentives to ensure the security of supply, and CRMs are expected to mitigate the risk of failure. Unfortunately, the numerous real world experiences have led to limited academic publications. In addition, the abundant theoretical literature fails to deliver clear take away messages with respect to the performance of CRMs in real life conditions. The empirical assessment of CRMs is all the more necessary as their performance depends on a number of country-specific, structural, technical and behavioral parameters, as well on the details of implementation that structure the incentives. Reducing the literature gap from both ends, this doctoral thesis represents the first attempts to empirically discuss CRM performance and design choices. It provides a conceptual reflection on the evolution of CRM designs over time (Chapter 1) and discusses the divergences existing in the quantitative literature (Chapter 2). It also contributes to the discussion on the net cost of such intervention thanks to an econometric cross-country analysis (Chapter 4). From a theoretical standpoint, an analytical model analyses the preferences for the precision of information available under different capacity market designs (Chapter 3).

KEYWORDS

Electricity markets, Capacity remuneration, Market design, Security of supply, Information provision in regulation, Cross-country analysis, Regulation