Electricity investments and development of power generation capacities : An approach of the drivers for investment choices in Europe regarding nuclear energy

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ET MANUFACTURES
« ÉCOLE CENTRALE PARIS »

THÈSE

présentée par

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pour l'obtention du

GRADE DE DOCTEUR

Spécialité : Génie Industriel
Laboratoire d'accueil : Laboratoire de Génie Industriel

SUJET :
Electricity investments and development of power generation capacities: an approach of the drivers for investment choices in Europe regarding nuclear energy.

Investissements électriques et développement de capacités de production d'électricité : une approche des déterminants des choix en Europe en matière de nucléaire

soutenue le : 07 mars 2014

devant un jury composé de :

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2014ECAP0025

Abstract

In a context of growing energy demand and environmental concerns (Fukushima accident and climate change mitigation), the thesis addresses the issue of investments in power generation capacities and in particular nuclear capacities. Given that the Generation IV of nuclear reactors is supposed to be ready in 2040 for industrial deployment, the purpose of the thesis is to study the conditions for electricity investments in France and Europe within this horizon, in order to assess development perspectives for nuclear energy and for potential emergence of Generation IV on the European market. To do so, it is necessary to study the mechanisms at stake in investment choices taking into account all power generating technologies. Economic theory usually bases the choice on long-term economic rationality, which does not allow explain the actual choices observed in European electricity mix. The objective of the research work is thus to identify investment choice drivers and to propose an approach describing the behavior of investors in a more realistic way. A multidisciplinary approach was adopted to explore the question. It combines a historical analysis of drivers evolution according to historical context, a structural analysis of these drivers to identify favorable scenarios for future nuclear reactors, a value creation approach to replicate investors' preferences in those scenarios, and last, a value option approach focusing on nuclear technologies and comparing competitiveness of Generation IV reactors with current reactors. As a result, industrial development of Generation IV appears highly dependent on strong climate policy combined to government support to nuclear, and not much impacted by market deregulation or cost evolution of technologies, which shows the failure in bringing the market to effective competition. In particular high progress of renewables does not lessen the attractiveness of nuclear energy.

Keywords : Power System Economics, Electricity Investments, Nuclear Energies, European Electricity Market, European Strategic Foresight, Value Creation, Design Structure Matrix, Option Value

Résumé

Dans un contexte de forte croissante de la demande énergétique comme des préoccupations environnementales (protection du climat, accident de Fukushima), la thèse s'intéresse à l'investissement dans des capacités électrique, en particulier dans le nucléaire. Partant de l'hypothèse où la Génération IV de réacteurs nucléaires serait prête autour de 2040 pour un déploiement industriel, l'objet de la thèse est d'analyser les conditions d'investissement et de développement de capacités de production d'électricité en France et en Europe à cet horizon, afin d'évaluer les perspectives de développement du nucléaire sur le marché électrique européen et le potentiel développement de la Génération IV. Pour ce faire, le travail de recherche nécessite de prendre du recul et d'étudier de manière générale, en prenant en compte toutes les technologies de production d'électricité, les mécanismes entrant en jeu dans le choix d'investissement de l'électricien lorsqu'il s'agit de renouveler ou d'étendre son parc de production. L'approche économique classique basant généralement le choix de l'investisseur sur une rationalité économique de long terme, elle ne permet pas d'expliquer les choix effectifs constatés dans les mix électriques d'un pays à l'autre. L'objectif de cette thèse est d'identifier les déterminants des choix d'investissement dans des capacités électriques et de proposer une approche permettant de décrire le comportement du choix de l'investisseur allant au-delà du critère classique de rationalité économique de long terme. Une approche pluridisciplinaire a été adoptée pour répondre à la question posée. Elle combine une analyse historique de l'évolution des déterminants des choix en fonction du contexte, une analyse structurelle permettant d'identifier les scénarios les plus favorables à l'émergence de futurs réacteurs nucléaires, une approche de création de valeur permettant proposant de reproduire les préférences des électriciens en fonction des déterminants, et enfin une approche par la théorie des options réelles pour comparer les compétitivités respectives des futurs réacteurs nucléaires de Génération IV avec celle des réacteurs actuels. Il en résulte que le passage effectif à la Génération IV apparaît fortement dépendant de la politique climatique et du soutien au nucléaire, et peu impacté par la libéralisation du marché européen comme par les évolutions de coûts des technologies, signe de l'échec de la création d'un marché compétitif de l'électricité en Europe. Notamment, de fort progrès technologiques dans le domaine des renouvelables ne sont pas antinomiques avec le développement de nouveaux réacteurs.

Mots-clés : Economie des systèmes électriques, Investissements électriques, Energie nucléaire, Marché électrique européen, Prospective, Création de Valeur, Design Structure Matrix, Valeur d'option

L’avenir, tu n’as pas à le prévoir, mais à le permettre.

Antoine de Saint-Exupéry

Citadelle, éd. Gallimard, coll. NRF, 1948, chap. LVI, p. 167

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Acknowledgements/Remerciements

Ce travail de thèse a été réalisé au Commissariat à l'Energie Atomique et aux Energies alternatives (CEA Saclay), avec l'encadrement académique de l'Ecole Centrale Paris.

Je souhaiterais tout d'abord remercier mes cinq encadrants : M. Jean-Claude Bocquet, Directeur du Laboratoire de Génie Industriel, directeur de thèse, pour avoir assumé la direction scientifique de mon travail avec un œil clairvoyant et des conseils toujours avisés ; M. Jean-Guy Devezeaux de Lavergne, Directeur de l'Institut de Technico-Economie des Systèmes Energétiques (I-tésé) au CEA, encadrant CEA, pour avoir suivi et fortement soutenu le déroulement ainsi que la diffusion de mes travaux, au sein du CEA comme à l'extérieur ; M. Pascal Da Costa, Maître de Conférences à l'Ecole Centrale Paris, co-directeur de thèse, pour son expertise économique, son suivi quotidien, sa direction précise et efficace concernant l'avancement et la diffusion des travaux, et nos collaborations fructueuses ; Mme Danièle Attias, Professeur à l'Ecole Centrale Paris, co-directrice de thèse également, pour son suivi académique et son regard enrichissant sur mes travaux ; M. Gilles Mathonnière, ingénieur-chercheur à l'I-tésé, co-encadrant CEA, pour m'avoir initiée aux sujets nucléaires et pour son accompagnement dans tous les travaux internes au CEA. Merci à tous pour votre engagement à mes côtés durant ces trois années, votre disponibilité, votre bonne humeur et votre soutien.

J'adresse mes remerciement sincères aux membres du jury : M. Jacques Percebois, Professeur d'Economie à l'Université Montpellier I, Directeur du Centre de Recherche en Economie et Droit de l'Energie (CREDEN), qui préside ce jury, ainsi que MM. Patrick Criqui, Directeur de recherches CNRS, Directeur du laboratoire LEPII, CNRS-Université Pierre Mendès-France, et Patrice Geoffron, Professeur d'Economie à l'Université Paris-Dauphine, Directeur du Centre de Géopolitique de l'Energie et des Matières Premières (CGEMP), qui ont accepté d'être les rapporteurs de ce travail de thèse. Je suis très honorée que vous ayez accepté de juger ce travail et de faire partie du jury.

Je souhaiterais également remercier Mme Nathalie Popiolek, expert senior à l'I-tésé, pour notre collaboration fructueuse sur un chapitre de cette thèse ; je lui suis extrêmement reconnaissante de m'avoir incluse dans ses travaux, de m'avoir consacré son temps et fait bénéficier de sa pédagogie.

J’exprime toute ma gratitude aux experts qui ont accepté d’être interviewés pour cette étude : MM. Yves Kaluzny, Jean-Claude Perraudin, Pascal Anzieu, Laurent Joudon, Christian Fontanel, Bertrand Barré, Christophe Bonnery, Patrick Darmon, le Département des Relations Internationales du CEA ainsi que le réseau des conseillers nucléaires dans les ambassades de France.

Je souhaite remercier chaleureusement Romain Farel et Yann Leroy, enseignant-chercheurs au Laboratoire de Génie Industriel, pour leurs explications, leurs connaissances et leurs conseils dans les domaines liés à la conception innovante.

Merci à Christine Mansilla de m’avoir accueillie et encadrée en stage de fin d’études et de m’avoir ainsi ouvert les portes de l’I-tésé, ainsi que de son soutien en tant que collègue durant les trois années de thèse qui ont suivi.

Je remercie M. Yves Amalric, correspondant informatique à l’I-tésé, pour son aide précieuse sur les sujets informatiques.

J’exprime toute ma reconnaissance à la formidable équipe de l’I-tésé au sein de laquelle j’ai eu beaucoup de plaisir à travailler : Patricia pour son dynamisme et son efficacité à toute épreuve, Françoise, Anne, Sophie G., Alain, Thierry, Séverine, Didier, et le reste de l’équipe pour leur gentillesse au quotidien, sans oublier Sophie A. et Frédéric.

J’adresse des remerciements particuliers aux doctorants (passés et présents) de l’I-tésé : Camille, Julie, Anton et Antoine, avec qui j’ai été très heureuse de partager cette expérience de thèse.

Je remercie également toute l’équipe du LGI pour leur sympathie et leur accueil, en particulier Sylvie, Corinne et Delphine pour leur aide, ainsi que tous les doctorants et chercheurs avec qui j’ai discuté et partagé de bons moments, en particulier Wenhui et Hakim.

J’adresse mes remerciements sincères au personnel de l’INSTN pour m’avoir permis de suivre des cours du master de Génie Atomique pour ma formation doctorale : Joseph Safieh, Constance Coston, et Leila Gicquel.

Je remercie également Christophe Cahn, enseignant à l’Ecole Centrale Paris, pour m’avoir permis de suivre son cours « Modélisation Macro-Economique Moderne ».

Enfin je souhaite remercier ma famille, mon compagnon et mes amis pour leur soutien et leurs encouragements durant ces trois années.

Extended summary/Résumé étendu

(Extended summary in French)

1. Contexte et question de recherche

Dans un contexte de forte croissante de la demande énergétique comme des préoccupations environnementales (protection du climat, accident de Fukushima), la thèse s'intéresse à l'investissement dans des capacités électrique, en particulier dans le nucléaire. Partant de l'hypothèse où la Génération IV (Gen IV) de réacteurs nucléaires, identifiée comme la technologie des réacteurs à neutrons rapides refroidis au sodium, serait prête autour de 2040 pour un déploiement industriel, l'objet de la thèse est d'analyser les conditions d'investissement et de développement de capacités de production d'électricité en France et en Europe à cet horizon, afin d'évaluer les perspectives de développement du nucléaire sur le marché électrique européen et le potentiel passage à la Génération IV.

Pour ce faire, le travail de recherche nécessite de prendre du recul et d'étudier de manière générale, en prenant en compte toutes les technologies de production d'électricité, les mécanismes entrant en jeu dans le choix d'investissement de l'électricien lorsqu'il s'agit de renouveler ou d'étendre son parc de production. L'approche économique classique base généralement le choix de l'investisseur sur une rationalité économique de long terme, à savoir la minimisation du coût du kWh ou la maximisation du profit espéré, cependant cette approche ne permet pas d'expliquer la disparité observée entre les mix électriques d'un pays à l'autre. Il s'agit ici d'aller au-delà de cette approche et d'analyser les politiques énergétiques, les évolutions technologiques, les particularités des marchés qui vont peser sur la décision d'investissement, afin de répondre aux questions de recherche suivantes :

Quels sont les facteurs qui motivent les décisions des électriciens européens en matière d'investissement et de développement de capacités de production ?

Comment orientent-t-iles l'évolution du mix européen à moyen et long terme, et avec quelles conséquences sur le nucléaire ?

2. Objectifs

Les objectifs de cette thèse sont les suivants :

- identifier les déterminants des choix d'investissement dans des capacités de production d'électricité,
- proposer une approche permettant de décrire le comportement du choix de l'investisseur allant au-delà du critère classique de rationalité économique de long terme,
- en déduire les scénarios les plus favorables au développement du nucléaire sur le marché européen et les conditions nécessaires pour le passage à la Génération IV.

En termes de périmètre, l'étude choisit de se limiter aux 5 pays les plus producteurs et consommateurs d'électricité, à savoir : la France, le Royaume-Uni, l'Allemagne, l'Italie, l'Espagne.

3. Approches et résultats

Une approche pluridisciplinaire a été adoptée pour apporter différents éclairages à la question posée.

1. Analyse historique et théorique

Une analyse historique de l'évolution des déterminants des choix d'investissements sur le marché électrique européen a été menée sur la période des années 50 à aujourd'hui, identifiant les déterminants de l'investissement et leur évolution en fonction du contexte. Il apparaît que si le courant marginaliste a imposé des décisions d'investissements basées sur la rationalité économique de long terme pour certains pays dans les années 50 et 60 notamment en France (Boiteux, 1971; Massé, 1953), d'autres déterminants relevant d'un opportunisme de court terme ont régulièrement pris le pas sur cette rationalité économique : sécurité énergétique, protectionnisme économique, et aujourd'hui, préoccupations environnementales (Chick, 2007; Grand and Veyrenc, 2011). La libéralisation du marché électrique européen censée remettre cette rationalité économique au cœur de la gestion du marché électrique n'a pas connu de franc succès, puisque l'on observe un retour à des pratiques centralisées même dans les pays pionners de la libéralisation comme le Royaume-Uni (Percebois and Wright, 2001; Percebois, 2013).

2. Prospective : analyse structurelle et scénarios

Dans la continuité de l'analyse historique, une méthode de prospective : l'analyse structurelle (Coates et al., 2010; Durance and Godet, 2010; Godet, 2010, 2000), a été utilisée pour creuser l'identification des déterminants d'investissement et de leurs interactions. Cette analyse a permis de d'identifier 4 groupes de déterminants décomposés en 26 déterminants :

- Les déterminants liés à la politique des Etats : politique climatique (CO_2 et renouvelables) et politique nucléaire
- Les déterminants liés au marché et à ses acteurs : création d'un marché libéralisé, financements privés
- Les déterminants liés à l'évolution technologique : coût de construction et de production, caractéristiques techniques
- Les déterminants liés à l'électricien investisseur : profil privé ou public, taille de l'entreprise (capitalisation, capacité installée, production, chiffre d'affaire), portefeuille technologique de l'entreprise

Ces déterminants sont listés de manière détaillée dans le Tableau A ci-dessous.

Déterminants	Type de déterminant	Partie prenante associée
Taxe carbone (€/tCO_2)	Déterminants politiques	Acteurs étatiques : gouvernement, ministères, Union européenne
Quota carbone		
Tarif d'achat renouvelables (€/MWh)		
Certificat vert		
Appel d'offre pour renouvelable		
Incitation fiscale pour renouvelable		
Position nucléaire		
Strike price pour le nucléaire (€/MWh)		
Stabilité de la politique		
Indice de concentration IHH	Déterminants marché	Acteurs du marché : o Concurrents o Gestionnaire de réseau o Régulateurs o Organisme de financement
Développement du réseau et des interconnexions		
Corporate financing		
Project financing		
Financement hybride		
Méthode de financement originale		
Coût de construction (€/MW)	Déterminant changement technologique	Développeurs de technologies
Coût de production (€/MWh)		
Durée de construction (années)		
Capacité d'une centrale (MW)		
Facteur de charge (%)		
Structure de l'actionnariat	Déterminants internes à l'entreprise	Entreprise d'électricité
Capitalisation boursière		
Production annuelle		
Mix de production		
Part de marché		
Chiffre d'affaires		

Tableau A : Liste des déterminants de l'investissement électrique et des parties prenants associées

L'étude des interactions entre déterminants par l'analyse structurelle a permis de les hiérarchiser et d'identifier, parmi les scénarios possibles, les plus favorables à l'émergence de futurs réacteurs nucléaires sur le marché, schématisés en Figures A et B. Le déterminant de la politique climatique apparaît comme le plus critique et est donc au cœur des scénarios retenus.

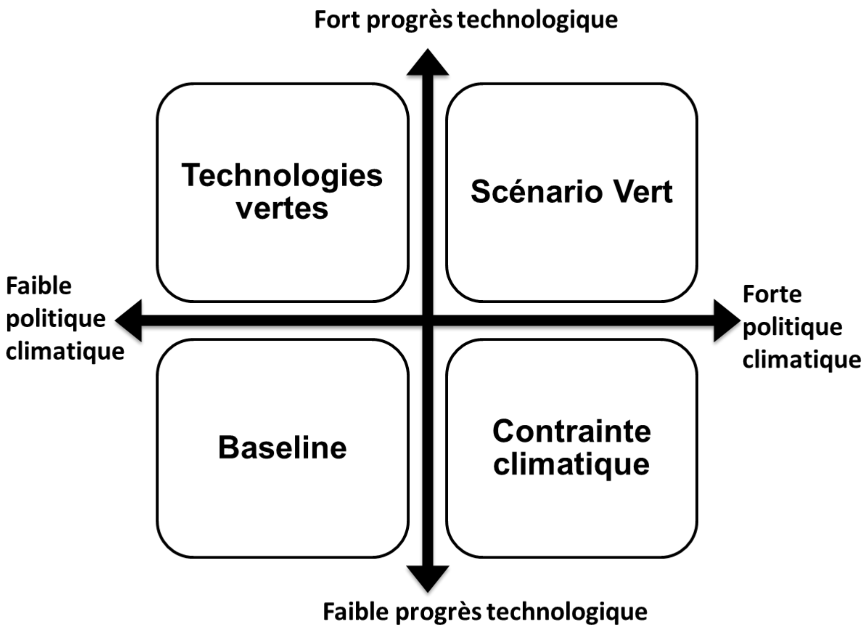


Figure A. Scénarios construits selon les hypothèses hautes et basses pour le progrès technologique et la politique climatique

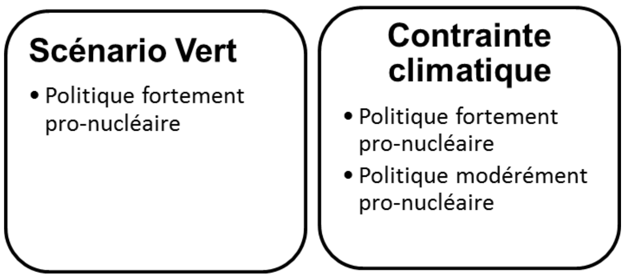


Figure B. Scénarios identifiés comme les plus favorables au nucléaire et à la Génération IV

3. Approche par la création de valeur

Une approche de création de valeur permet ensuite de construire un outil matriciel proposant de reproduire les préférences des électriciens en fonction des déterminants. Les parties prenantes associées à chaque type de déterminant sont définies ainsi que la valeur qu'elles recherchent lors de la décision d'investissement dans une capacité de production d'électricité. Il en résulte que pour maximiser la création de valeur qu'elle recherche, l'entreprise électrique doit choisir la technologie qui maximise l'adéquation entre les déterminants internes à l'entreprise et les autres déterminants. Un outil matriciel appelé matrice de compatibilité est construit afin de calculer pour un couple entreprise-technologie un indice de compatibilité, permettant ainsi de reproduire les préférences d'une entreprise en termes de technologies dans un scénario donné. A titre d'exemple, les préférences pour l'entreprise EDF dans le contexte français sont données ci-dessous pour les trois scénarios retenus.

Contrainte climatique
Politique pro-nucléaire modérée

FRANCE	EDF	
2010-2025		
	wind	0,65
	solar	0,59
	nuclear	0,52
	gas	0,50
	coal	0,43
2025-2040		
	wind	0,54
	nuclear	0,49
	gas	0,48
	coal	0,45
	solar	0,43

Contrainte climatique
Politique pro-nucléaire forte

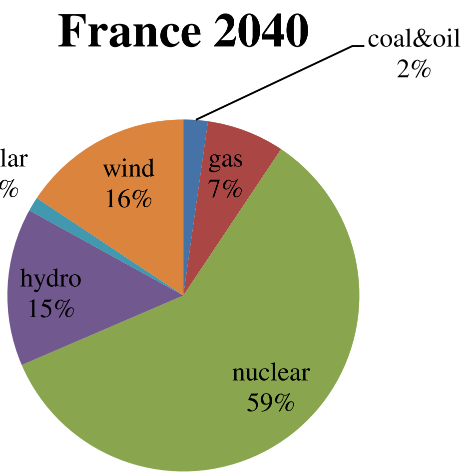
FRANCE	EDF	
2010-2025		
	wind	0,65
	solar	0,59
	nuclear	0,57
	gas	0,50
	coal	0,43
2025-2040		
	nuclear	0,57
	wind	0,54
	gas	0,48
	coal	0,45
	solar	0,43

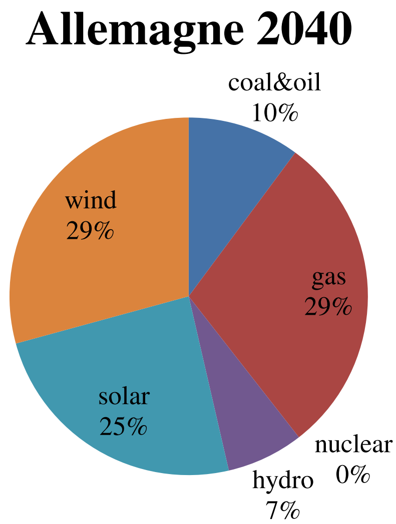
Scénario vert
Politique pro-nucléaire forte

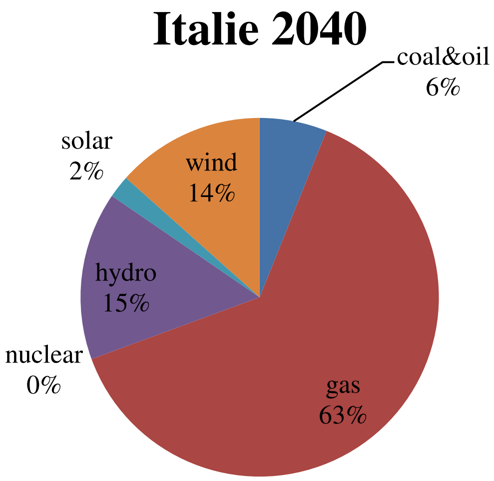
FRANCE	EDF	
2010-2025		
	wind	0,65
	solar	0,59
	nuclear	0,57
	gas	0,50
	coal	0,43
2025-2040		
	nuclear	0,57
	wind	0,56
	gas	0,49
	solar	0,47
	coal	0,44

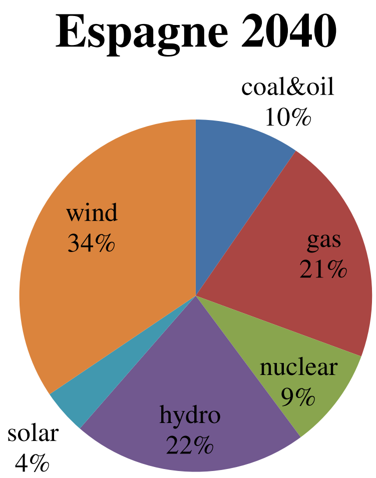
Tableau B : Indice de compatibilité pour EDF et les technologies étudiées dans les trois scénarios retenus

L'application de cet outil aux principaux électriciens européens dans le périmètre étudié permet de constater quelles seraient leurs préférences dans les scénarios identifiés comme favorables. Les résultats en termes de mix pour deux scénarios contrastés : « Contrainte climatique/Politique pro-nucléaire modérée », et « Scénario vert/Politique pro-nucléaire forte » sont montrés ci-dessous en Figures C et D.


France 2040
coal&oil 2%
gas 7%
nuclear 59%
hydro 15%
solar 1%
wind 16%


Allemagne 2040
coal&oil 10%
gas 29%
nuclear 0%
hydro 7%
solar 25%
wind 29%


Italie 2040
coal&oil 6%
gas 63%
nuclear 0%
hydro 15%
solar 2%
wind 14%


Espagne 2040
coal&oil 10%
gas 21%
nuclear 9%
hydro 22%
solar 4%
wind 34%

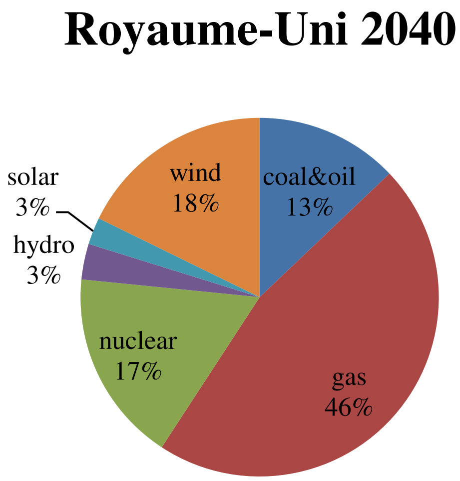

Royaume-Uni 2040
coal&oil 13%
gas 46%
nuclear 17%
hydro 3%
solar 3%
wind 18%

Figure C : résultats en termes de mix pour le scénario « Contrainte climatique/Politique pro-nucléaire modérée ».

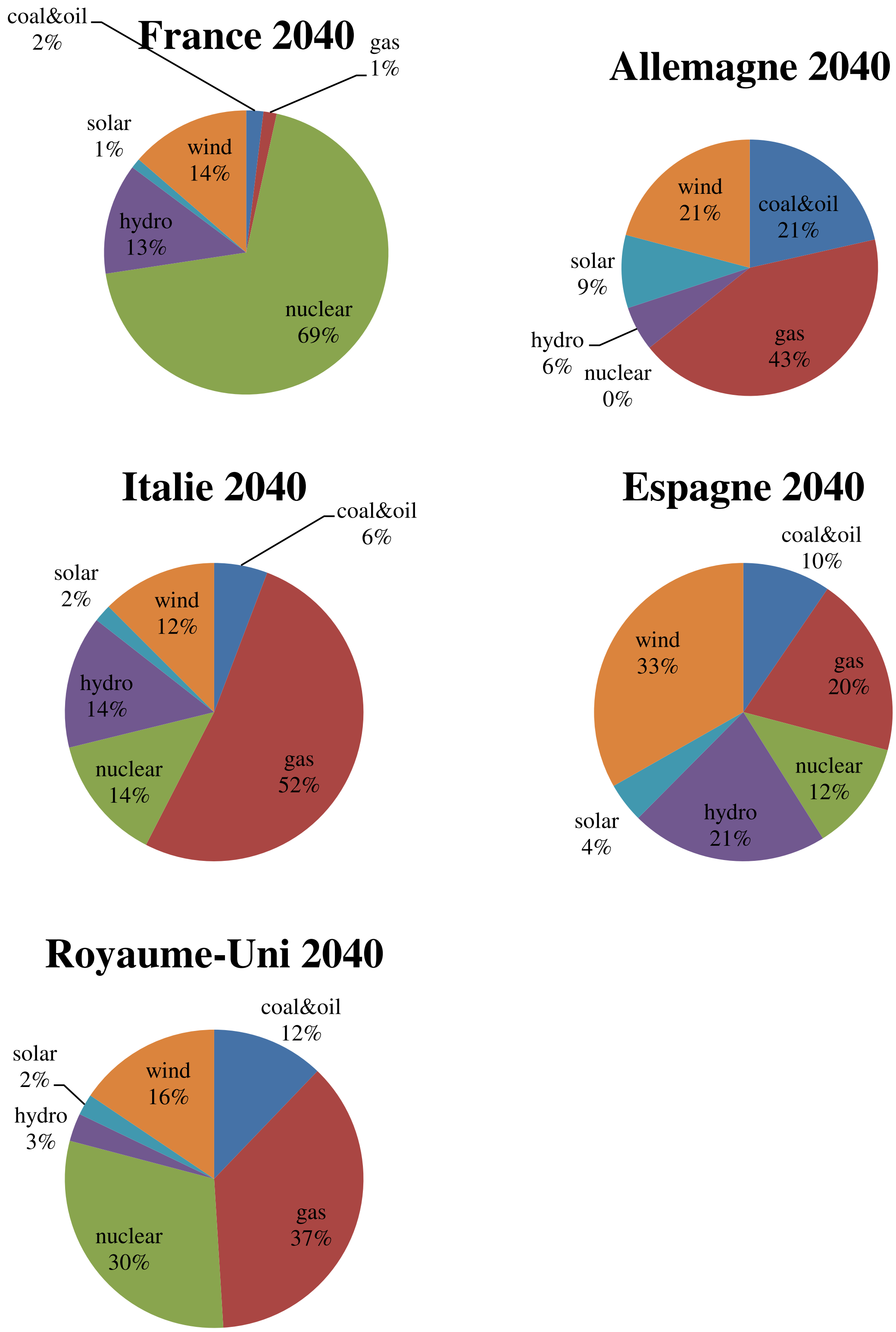


Figure D : résultats en termes de mix pour le scénario « Scénario vert/Politique pro-nucléaire forte »

Il en résulte que l'émergence des réacteurs sur le marché apparaît finalement fortement dépendante des politiques pro-nucléaires comme d'une politique climatique forte, mais peu impactée par les réductions de coûts des autres technologies. En effet, de fort progrès technologiques dans le domaine des renouvelables ne sont pas antinomiques avec le développement de nouveaux réacteurs.

4. Analyse d'une valeur d'option

Se focalisant plus sur le nucléaire et la France, une approche par la théorie des options réelles (Claude Henry, 1974) a permis de comparer les compétitivités respectives des futurs réacteurs nucléaires de Génération IV avec celle des réacteurs actuels. En effet, en cas de tensions sur le marché de l'uranium (OECD and IAEA 2012), la technologie des réacteurs à neutrons rapides Gen IV (RNR) offre une alternative durable grâce à sa meilleure utilisation de l'uranium. Néanmoins, cette technologie s'annonce plus coûteuse que ne l'est actuellement celle des réacteurs à eau légère (REL) qui constituent la majorité du parc actuel. Elle ne sera donc compétitive que si, malgré ce surcoût, l'augmentation du prix de l'uranium rend l'exploitation des REL plus chère que celle des RNR. Les deux paramètres clés dont dépend la compétitivité des RNR par rapport aux REL apparaissent grâce à cette analyse : il s'agit du surcoût du RNR par rapport au REL (surcoût en production, c'est-à-dire en coût du MWh), et l'augmentation anticipée du prix de l'uranium.

En prenant en compte les incertitudes sur les coûts futurs des deux types de réacteurs par une approche probabiliste, les coûts de fonctionnement du parc nucléaire sont évalués dans le cas d'une pénétration possible et sans pénétration possible de la Génération IV. La différence entre ces deux coûts constitue la valeur d'option de la technologie RNR : tant que le coût évalué pour le parc nucléaire sans Gen IV est supérieur au coût évalué pour le parc nucléaire avec Gen IV, cette valeur d'option est positive et poursuivre la recherche sur les RNR présente un intérêt économique. La Figure E établit une cartographie de cette valeur d'option dans différents cas de surcoût RNR et d'augmentation du prix de l'Uranium.

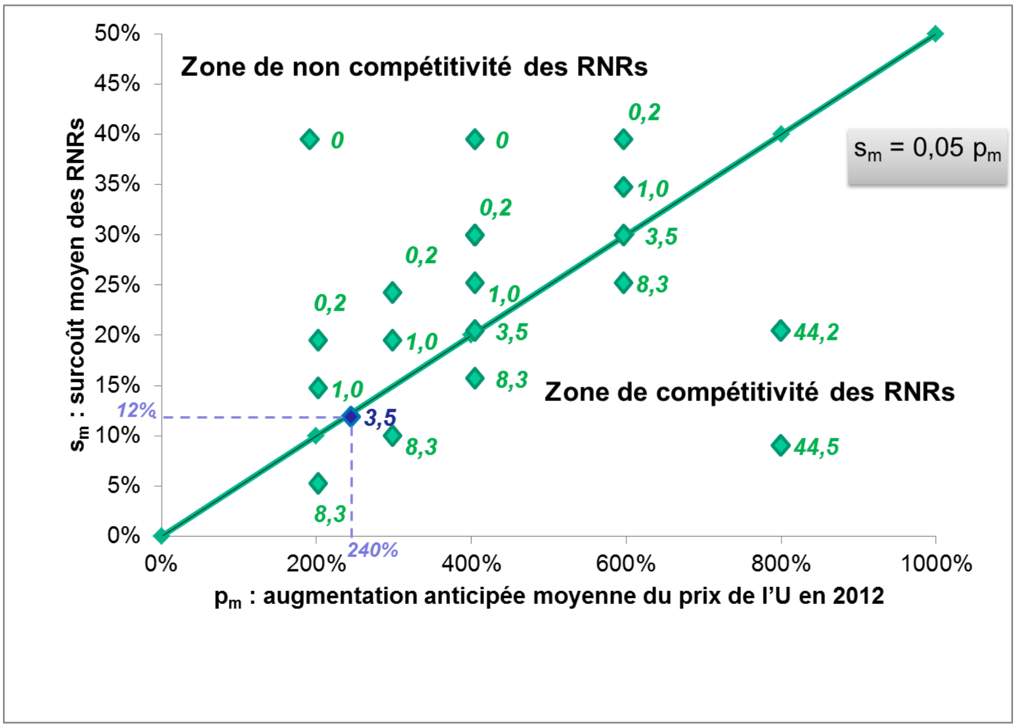


Figure E : cartographie des valeurs d'option pour plusieurs couples (surcoût RNR, augmentation du prix de l'uranium)

Le modèle permet de mettre en valeur le résultat suivant : en présence d'incertitude quant au surcoût des RNR et au prix futur de l'uranium, la valeur d'option associée à la décision de faire de la recherche prend des valeurs non nulle même dans la zone où le RNR est a priori non compétitif. Ce résultat est conforté par des simulations faisant varier l'incertitude, lesquelles ont montré que la valeur d'option augmentait avec l'ampleur de l'incertitude.

Il apparaît que l'option apporte une couverture contre de potentielles élévations des coûts des réacteurs actuels et que développer la technologie Génération IV répond à une rationalité économique de long terme.

4. Conclusions

Différentes approches méthodologiques ont permis d'identifier les déterminants de l'investissement électrique sur le marché européen et quel est le potentiel de pénétration des futurs réacteurs nucléaires sur ce marché. Ces approches complémentaires offrent l'avantage de brosser un tableau plus complet des déterminants des choix d'investissements que ne l'avait fait jusque-là l'approche Coût-Bénéfices classique et ainsi d'analyser plus finement les choix des électriciens. En retour, elles permettent de formuler des recommandations plus pertinentes quant aux mesures politiques à mettre en œuvre pour déclencher les réactions appropriées auprès des entreprises.

Les résultats des différentes approches menées montrent que les électriciens cherchent à s'assurer une sécurité économique de long terme, mais saisissent sans cesse des opportunités économiques de court terme qui paraissent à un moment donné lui offrir cette sécurité économique de long terme. Par conséquent, l'affichage d'une politique climatique comme d'une politique pro-nucléaire fortes, donc structurée sur le long terme, devraient rapidement lancer de futurs investissements nucléaires et permettre le passage à la Gen IV au moins en France et au Royaume-Uni ; en revanche, d'hypothétiques futures baisses de coûts dans les technologies ainsi que les effets escomptés de la dérégulation du marché européen ont bien moins d'impact sur les choix d'investissement des électriciens, ce qui met en évidence l'échec, pour l'instant, d'établir un marché interne de l'électricité compétitif en Europe. Les résultats obtenus pour les cinq pays étudiés sont directeurs au niveau européen ; il en résulte que les futurs investissements nucléaires sont globalement très dépendants de l'efficacité de la politique climatique européenne. Néanmoins, cette politique européenne est indissociable de la politique climatique internationale et repose donc en grande partie sur le succès des prochaines négociations climatiques internationales. Par ailleurs, l'approche méthodologique conduite ici pourrait être élargie à un niveau international en prenant en compte les déterminants spécifiques aux autres régions du monde, comme la forte croissance de la demande en électricité des pays émergents.

Introduction: Context and Problem setting

1 Context

1.1 Energy challenges for today and tomorrow

Yesterday, the major energy concerns lied in resources allocation and quantitative issues. After the first oil shock in 1973, international cooperation was built in order to ensure security of supply as much as possible, through the creation of the International Energy Agency. This paradigm came to know deep changes over the past decades, especially with growing awareness of environmental concerns from the 1990s thanks to the publication of the first IPCC report (IPCC, 1990). Under the auspices of the United Nation, international cooperation focused on climate change mitigation measures with the Kyoto protocol in 1997 and the following initiatives such as the creation of a carbon trading market in Europe (EU ETS[1]) and then the EU Energy Climate Package. One striking sign is the shift that from oil issues to climate issues in IEA publications like World Energy Outlook that was observed about fifteen years ago. Moreover, whereas energy access used to be the privilege of the most developed countries, globalization and global economic development made energy a good of prime necessity.

Today, global aspirations regarding in the energy sector consist in three pillars: energy access, energy security, and environmental sustainability. They are described by the World Energy Council as the 'Energy trilemma' (WEC, 2013a), since pursuing these three goals at the same time requires complex compromises. These aspirations are constantly confronted to mutations reshuffling the cards of resources availability or technology attractiveness. As Pierre Gadonneix said in the WEC 2013 Congress Statement, "Incidences such as Fukushima have all caused many countries reevaluate their energy strategies". Recently, three major events affected deeply the energy sector: the financial crisis, putting an important pressure on energy competitiveness, the development of unconventional

[1] European Union Emission Trading Scheme

hydrocarbons, changing the prospects of security of supply, and the Fukushima accident occurring at the dawn of a nuclear renaissance. At the same time, the climate change issue is making the need for action more and more urgent as last IPCC report shows (IPCC, 2013), while the international community still fails to reach an agreement on global measures for GHG emissions mitigation.

Future trends also bring their share of challenges, since at the current pace energy demand is expected to increase and could almost double by 2050, as well as global greenhouse gas emissions (WEC Congress Statement, 2013). According to World Energy Council scenarios, global energy demand could increase by up to 61% and GHG emissions by up to 45% between 2010 and 2050 in the baseline scenario "Jazz" (WEC, 2013b). In IEA's Energy Technology Perspectives scenarios, the 6°C scenario[2] (baseline scenario) expects energy demand to grow by 76% and GHG emissions by 83% by 2050. In the World Energy Outlook, the "Current Policies" scenario projects a 30% increase of global energy demand and 38% increase of GHG emissions by 2035, which is basically consistent with ETP 6°C scenario (IEA, 2013). However, scenarios with stronger policies regarding climate and energy show that such an outcome is avoidable: the WEC "Symphony" scenario assesses global energy demand to increase by 27% and GHG emissions to decline by 37%(WEC, 2013b). In ETP, two scenarios of climate change mitigation are considered: in the 4°C scenario, global energy demand increases by 60% and GHG emissions by 29%; in the 2°C scenario, global energy demand grows by 40% and GHG actually decrease by 16% (IEA, 2012a). Further comparison with World Energy Outlook scenarios outcomes in 2035 also shows consistency between ETP and WEO sets of scenarios[3]. The "New Policies" Scenario expects global energy demand to increase by 25% and GHG emissions by 19% by 2035; the "450ppm" scenario expects global energy demand to increase by 12% and GHG emissions to decrease by 14% by 2035 (IEA, 2013). Trends are globally similar, although they seem to get slightly enhanced after 2035.

Despite high growth of renewable share in the global energy mix, demand will still rely strongly on fossil fuels in 2050 in most of the quoted scenarios: 77% of the mix for the "Jazz" scenario and 59% in the "Symphony" scenario (WEC, 2013b); 54% of the mix in the ETP 6°C scenario, 43% in the 4°C scenario, and 29% in the most astringent scenario, the 2°C scenario (IEA, 2013). Available reserves are increasing drastically thanks to discovery of new resources, release of unconventional

[2] The 6°C scenario is the scenario in which global average temperature at the surface of the Earth is expected to increase by 6°C compared to pre-industrial era (1861–1880 period).

[3] In WEO, the "Current Policies" scenario is consistent with the ETP 6°C scenario, the "New Policies" Scenario is consistent with the ETP 4°C Scenario, and the "450ppm" scenario is consistent with ETP 2°C scenario.

hydrocarbons and efficiency improvements in classic exploitations. Although proven reserves could ensure 54 years of oil supply and 61 years of natural gas supply, total recoverable remaining resources bring these figures to 178 years for oil and 233 years for natural gas (IEA, 2013).

Energy poverty may still last, with one billion probably lacking access to electricity in 2030 (0,969 billion in the New Policies scenario(IEA, 2013) and half a billion in 2050: 0,3 billion in WEC “Jazz” scenario and 0,5 in the “Symphony” scenario (WEC, 2013b).

Last but not least, business and market models are ineffective in coping with current mutations on the sector, and a lack of capital is holding the necessary investments, making deep reforms necessary to break the deadlock (WEC, 2013).

1.2 The case of nuclear energy

1.2.1 Nuclear energy confronted to mixed signals

The issue of nuclear development in such conditions is addressed in MIT publication *The future of nuclear power after Fukushima* (Joskow and Parsons, 2012). This report states that nuclear growth will not be significantly reduced, except in Germany and Switzerland, where a nuclear phase out was decided, and in Japan, where the commitment to nuclear energy is being questioned. It assesses the expected growth of nuclear power in the world fleet to be 1% per year through 2035 in OECD countries and 6% per year in non-OECD countries through 2035. However, in the context of such goals meeting such challenges, nuclear energy is confronted to mixed signals ‘between hope and fear’ (Chevalier et al., 2012). On the one hand climate change mitigation requires low carbon technologies; nuclear energy happens to be a mature one. In addition, it allows massive supply at competitive costs on the long-term to answer a growing demand. On the other hand, the Fukushima accident, provoked by a major natural catastrophe, questions the ability of nuclear energy to ensure safety and environment protection. Safety improvements are also likely to reduce economic attractiveness of the technology.

In 2012, nuclear energy generated 10% of electricity in the world (IAEA and Enerdata Statistics, 2013), 27% in Europe (Eurostat Statistics, 2013) and almost 80% in France (IAEA Statistics). Today, the thermal neutron technology represents the most common technology in use. It is the predominant technology used for Generation II reactors, which is to say, the majority of reactors currently in operation in the world. This technology has also been chosen for the Generation III reactors such as EPR (European Pressurized Reactor) , that are currently under construction in France (Flamanville), Finland (Olkiluoto) and China (Taishan).

Identified resources in uranium nevertheless allow about one century of generation with thermal neutrons reactors (OECD and IAEA, 2012) for the reactors currently in operation. Growth of the world's nuclear fleet could thus have an important impact on the demand for natural uranium, leading to uranium shortage. Beside the resource issue, the management of long-lived radioactive waste and safety are the other main preoccupations for nuclear industry. Therefore, the Generation IV of nuclear reactors is thus under development to address these issues. Under the framework of the Generation IV International Forum[4], six technologies have been identified as offering significant progress regarding uranium, waste and safety issues, but also economic competitiveness issues (GIF, 2002).

1.2.2 Future nuclear reactors

1.2.2.1 Basic notions on nuclear energy

In order to understand the technical characteristics of the reactors that will be mentioned in this paragraph, here is a very brief reminder of basic notions on nuclear energy. In power generation, the nuclear reactor uses the heat produced by fission reaction in order to boil water that drives a turbine to produce electricity. The fission reaction needs fissile material (Uranium 235, Uranium 233, Plutonium 239): it is provided in the core of the reactor by the fuel that is either the fissile material either a fertile material generating the fissile material (Thorium 232 generates Uranium 233 for instance). In thermal reactors, neutrons are slowed down by the “moderator” in order to facilitate fission reaction. When neutrons are slowed down they are called “thermal neutron”, and in the other case, “fast neutrons”. The heat produced by fission reaction is transported by a fluid for electricity generation purposes[5]: this fluid is the coolant. Sometimes coolant and moderator are the same fluid assuring both roles (for instance water in Light Water Reactors). A nuclear technology is generally defined by these three characteristics: fuel, moderator and coolant. However the terminology is often implied. In the case of fast neutrons reactors, there is of course no moderator; plutonium is

[4] Generation IV International Forum is an initiative launched by US government’s Department of Energy ensuring cooperation between several countries regarding the development of Generation IV Nuclear Reactors: United States, United Kingdom, Japan, France, Russia, Canada, Brazil, Switzerland, South Korea, South Africa, Argentina, and one institution: European Union

[5] In Boiling Water Reactors, the water serving as both moderator and coolant is heated and boils, the resulting steam directly allowing driving the turbine. In Pressurized Water Reactors, the coolant transports heat in a primary circuit in order to heat in a secondary circuit where boiled water’s steam drives the turbine. In Gas-cooled Reactors, the heated gas (coolant) drives the turbine.

usually implied to be the fuel. For thermal neutrons reactors, uranium is usually the fuel. In the case of most water reactors, coolant and moderator are the same.(Naudet et al., 2008)

1.2.2.2 Overview of generations of nuclear reactors

To replace this Generation of Nuclear Reactors among all generations of nuclear reactors, we draw a quick overview of generations of nuclear reactors from the beginning of nuclear power generation (cf Figure 1 below).

Generation I were the first prototypes built in the 1950s and 60s: the most famous ones are Shippingport (pressurized water reactor), Magnox (CO_2 cooled reactor using graphite as a moderator), Fermi I (sodium cooled fast reactor).

Generation II Reactors are the first commercial power plants built in the 1970s and still operating today. The most common technologies are Light Water Reactors (LWR), representing 88% of installed nuclear capacities in the world (IAEA, 2012). They include Pressurized Water Reactors (PWR), Boiling Water Reactors (BWR), Russian VVER (pressurized water reactors also). Other Generation II reactors are for instance CANDU reactors (heavy water reactors), Advanced Gas Reactors (AGR, cooled with CO_2 and using graphite as a moderator, like Magnox) or RBMK (light water reactors moderated with graphite).

Generation III Reactors were developed more recently in the 1990s, the technologies are pretty similar to Generation II technologies but with significant progress in safety and economics. This generation includes EPR: Evolutionary Pressurized Reactors (French design), that are currently under construction in France (Flamanville), Finland (Olkiluoto) and China (Taishan) but also Advanced Boiled Water Reactor (Japan), Système 80+ (Korea), AP1000 (American technology). They are likely to be built between now and 2030.

Generation IV reactors are the new designs expected to be deployed from 2040 and are currently under study (GIF, 2012, 2002) .

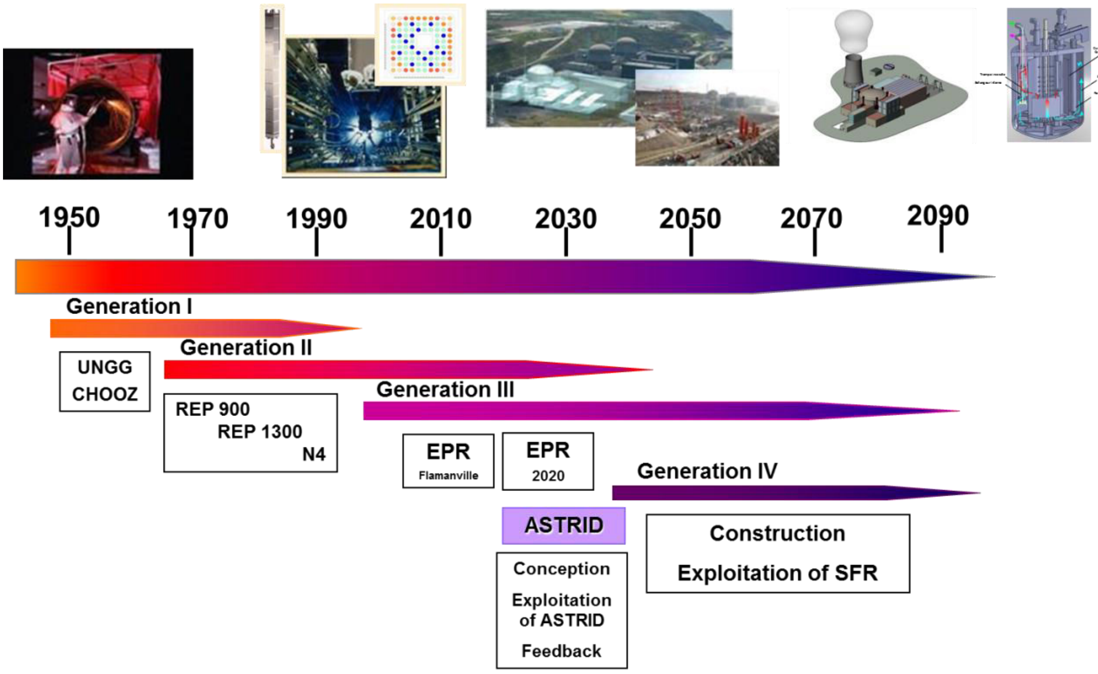


Figure 1: Generations of nuclear reactors (CEA 2011)

The future of nuclear energy will thus rely on both Generation III and Generation IV reactors, Generation IV being still at the stage of designing.

1.2.2.3 The technologies labeled as Generation IV nuclear reactors

In order to define the reactors of Generation IV, an international cooperation framework called the Generation IV International Forum (GIF) was built in 2001 by ten countries: Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States. They have been joined by Russia, China, and European nuclear initiative Euratom since then. The GIF established the following goals to be met for Generation IV reactors (GIF, 2002).

Sustainability
Generation IV nuclear energy systems should meet the following sustainability objectives: low GHG emissions, long-term availability of systems, effective fuel utilization, minimization of nuclear waste, and reduction of long-term stewardship for nuclear waste.
Economics
Generation IV nuclear energy systems should offer life-cycle cost advantages over other energy sources, and a level of financial risk comparable to other energy projects.
Safety and Reliability
Safety and reliability should be ensured, in particular through to low likelihood and degree of reactor core damage, and by eliminating the need for offsite emergency response.
Proliferation Resistance and Physical Protection
Generation IV nuclear energy systems should have strong assurances against diversion of weapons-usable materials, and provide increased physical protection against acts of terrorism.

Table I: Goals for Generation IV Nuclear Energy Systems (GIF 2002)

Six technologies were identified as the most relevant ones to meet these goals. They are cited below with the main characteristics.

Among the six Generation IV nuclear energy systems, three of them are fast reactors, and two of them can function as fast or thermal reactors.

Technology	Description
Sodium cooled fast reactors (SFR):	full actinide management and enhanced fuel utilization
Gas cooled fast reactors (GFR):	coolant is helium full actinide management and enhanced fuel utilization
Lead cooled fast reactors (LFR):	coolant is lead or lead-bismuth alloy full actinide management
Very high temperature gas reactors (VHTR):	cogeneration of heat and electricity coolant is helium thermal
Supercritical water cooled reactors (SCWR):	electricity generation at high temperatures thermal or fast
Molten salt reactors (MSR):	molten salt solution is both the coolant and the fuel liquid or solid fuel and full actinide management thermal (fuel: Thorium) or fast (fuel: Uranium or Plutonium)

Table II: Generation IV Nuclear Energy Systems (GIF 2002)

Among these six technologies, SFR is the reference technology for France since technical feasibility is acquired thanks to previous experience in the matter (RAPSODIE, PHENIX, SUPERPHENIX).

1.2.2.4 Interest in Fast Reactor worldwide: a key aspect for future of nuclear energy

Beside France, several countries are in interested in developing Fast Reactors, although not always in the frame of Generation IV label. In this paragraph, we give an overview of main research programs for fast reactors worldwide (source: *Wano website*).

In Western Europe, interest for Fast Reactors resides mainly in France. The chosen technology is the Sodium-cooled Fast Reactor (SFR), currently under study in French Commission for Atomic Energy and Alternative Energies (CEA). This program aims at building a 600 MWe prototype (ASTRID project) around 2020 in order to allow industrial deployment around 2040 (Ministère du Développement durable, 2013). In parallel, there is also a French interest in Gas-cooled Reactors as an alternative Generation IV nuclear technology with project ALLEGRO, a collaborative program with Central European countries. In the UK, there is no research program aiming at developing an industrial Fast Reactor. However policies and public opinion are favourable to nuclear energy in general, as the recent agreement for Hinkley Point EPRs shows (Department of Energy & Climate Change and Prime Minister's Office, 2013). There could thus be a commercial interest in industrial Fast Reactors later. On the other hand, a nuclear phase-out is planned in Germany, Switzerland and Italy.

In Central Europe, two research programs on Fast Reactors are currently being carried out. Project ALLEGRO for Gas-cooled Fast Reactor involves Hungary, Czech Republic and Slovakia, supported by a French collaboration; project ALFRED for a Lead-cooled Reactor is being carried out in Romania. These programs however do not plan an industrial deployment as soon as the ASTRID project does in France.

In Russia, interest in Fast Reactors is part of the national strategy to become a global leader in nuclear energy. Sodium-cooled reactors, lead-cooled reactors and lead-bismuth-cooled reactors are the chosen technologies, Sodium-cooled reactors being far ahead in their deployment since two have already been built (BN-350 and BN-600, respectively 350 MWe and 600 MWe). BN-800 is under construction and BN-1200 under study. Export of two BN-800 to China has also been planned.

In the United States, interest for Generation IV seemed to flourish in the early 2000s with the Generation IV International Forum in 2001 and the Gen IV program in 2003. However, potential radical change of policy every 4 years makes it difficult for energy policy to have long-term prospects.

There is a Fast Reactor research program in Japan that is pretty similar to the French one. It is aiming at building a Japanese Sodium Fast Reactor. However due to the Fukushima accident in addition to former technical problems on experimental SFR Monju, this program is on stand-by.

China's program for Fast Reactors is defined by the Chinese Institute of Atomic Energy (CIAE) and mainly based on Sodium-cooled technology. A small SFR of Russian design (25 MWe), the Chinese Experimental Fast Reactor (CEFR) is already operating. Two prototypes based on the same design are planned to be built around 2020 and 2030, the Chinese Demonstration Fast Reactor (CDFR, 1000MW) and then the Chinese Demonstration Fast Breeder Reactor (CDFBR, 1200 MW), that would meet the Generation IV requirements.

A fast reactor is also already in operation in India: the 13.5 MWe Fast Breeder Test Reactor (FTBR). The next prototype to be built is the 500 MWe Prototype Fast Breeder Reactor (PFBR). The Indian nuclear program plans to develop Fast Reactors to be able to operate thorium-fuelled reactors within a few decades, since thorium is very abundant on Indian territory.

In the global arena, interest for SFR is strong, revealing new players willing to take leadership in the nuclear sector. We can see that serious competitors to the French SFR are on their way of developing in Asia and Russia. The success of French SFR is thus a key factor to keep French nuclear leadership.

1.3 Power generation technologies beside nuclear energy

Nuclear energy is today mostly dedicated to power generation, although using it for heat is often considered. Beside nuclear energy, power generation relies worldwide on a panel technologies, the most commonly used on an industrial scale being: coal, gas, hydropower, wind, solar. Future development of nuclear energy in the electricity mix will depend not only on nuclear technologies performances but also largely on those of the other technologies in the portfolio. In order to assess potential development of the above-mentioned SFR technology in the power generation mix, the development perspectives of all power generation technologies are to be taken into account. In this section, we give an overview of current and future costs for these technologies.

1.3.1 *Current costs of technologies*

Technology costs calculations are to be found in IEA and NEA publications. The report 'Projected Costs of Generating Electricity' (OECD-NEA, 2010) gives the most detailed assessment of Levelized Costs of Electricity today, although exploitation of shale gas in the United States and massive importation of liquid gas in Japan after Fukushima have significantly modified generation costs from gas already. A summary of main values and technology characteristics for the median case among OCDE countries is given below.

median case specifications	nuclear	CCGT	SC/USC coal	coal </90% CCS	onshore wind	solar PV
capacity (MW)	1400	4800	750	474,4	45	1
owner's and construction	2517,85	696,36	1310,30	2282,48	1529,97	3939,40
overnight cost ($/kW)	2805,43	731,18	1459,31	2624,86	1606,47	4107,96
o&m ($/MWh)	10,08	3,06	4,12	9,31	14,99	20,49
fuel costs ($/MWh)	6,38	41,81	12,46	8,92	0,00	0,00
CO2 cost ($/MWh)	0,00	7,21	16,39	2,20	0,00	0,00
efficiency	33%	57%	41,1%	34,8%		
load factor	85%	85%	85%	85%	26%	13%
lead time	7	2	4	4	1	1
expected lifetime	60	30	40	40	25	25
LCOE ($/MWh) 5%	40,0	58,7	44,6	42,5	66,2	281,0
LCOE ($/MWh) 10%	67,5	63,0	54,8	61,5	93,8	421,7

Table III: Median LCOE for main technologies for OECD countries, converted from $ to €[6] (OECD-NEA, 2010)

[6] Used conversion rate : 0,684, as indicated in the report

WEO (IEA, 2012b) provides with a different manner of presenting costs: yearly kW costs.

Technology	Capital costs (€2011 per kW)	Yearly O&M Costs (€2011 per kW)
Coal	1436	44
Gas	594	18
Nuclear	2872	72
Hydropower	2201	46
PV	2344	23
Concentrating solar power	5141	206
Wind onshore	1213	18
Wind offshore	2448	73

Table IV: World Energy Outlook yearly costs - Europe average converted from $ to €[7] (IEA, 2012b)

In the report 'System Effects in Low-Carbon Electricity Systems', NEA shows that beyond generation costs, there are also system costs at stake, according to the level of penetration of each technology (OECD-NEA, 2012). This issue has become much more obvious with the increasing share of intermittent renewable energies that are the ones with the highest system costs. The table below sums up the assessed system costs for the main technologies in power generation.

€/MWh	Nuclear		Coal		Gas		Onshore wind		Offshore wind		Solar	
Penetration level	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%
Back-up costs	0,00	0,00	0,06	0,06	0,00	0,00	5,84	6,23	5,84	6,23	13,93	14,22
Balancing costs	0,20	0,19	0,00	0,00	0,00	0,00	1,36	3,60	1,36	3,60	1,36	3,60
Grid connection	1,28	1,28	0,67	0,67	0,39	0,39	4,98	4,98	13,38	13,38	11,47	11,47
Grid reinforcement	0,00	0,00	0,00	0,00	0,00	0,00	2,51	2,51	1,54	1,54	4,14	4,14
Total	1,49	1,47	0,73	0,73	0,39	0,39	14,70	17,30	22,14	24,75	30,90	33,42

Table V: System costs for power generating technologies according to different levels of penetration, converted from $ to €, French case

1.3.2 *Future trends*

As for future trends of these costs, World Energy Outlook (IEA, 2012b) and Energy Technology Perspectives (IEA, 2012a) assess that evolution is mainly to be expected on renewables:

Technology	ETP low change	ETP high change	WEO low change (New Policies scenario)	WEO high change (450 scenario)
Onshore wind	-12%	-20%	-4%	-6%
Offshore wind	-33%	-50%	-39%	-45%
Solar PV (utility and rooftop)	-57%	-63%	-47%	-53%
Concentrated solar power	-38%	-93%	-42%	-51%

Table VI: Comparison of expected kW cost reduction according to ETP (2020) and WEO (2035)

[7] Used conversion rate : 0,718, source : INSEE

According to these sources, no notable change is expected on nuclear, coal, gas, and hydropower, except for the variations due to fuel prices – coal, gas and uranium prices. However one must still bear in mind that such costs depend on context, especially for nuclear (Lévêque, 2013).

1.3.3 Generation cost: the main driver for technology choice?

The costs and performances presented in this section give a fair overview of relative competitiveness of power generation technologies. Despite local differences from one country to another, the median case in paragraph 1.3.1 is rather representative of costs in OECD countries. Given these costs and the performances associated to the technology (size and load factor), it is easy to deduce an optimal generation mix from the cost point of view in order to meet the demand, as in (Bibas, 2011) for instance. However, the fact is that major differences can be observed among OECD countries' power generation mix: France relies on nuclear power for 75% of its generation, Germany on coal for 47% of its generation, and Italy on gas for 57% (Grand and Veyrenc, 2011). Those three examples show that cost trends are insufficient to explain energy choices and thus future development of technologies. Future development of nuclear power will be driven not only by costs, but also other factors to be defined.

1.4 European context

The development of the French Generation IV technology, aka the SFR technology, is first expected on its local market: France, which is currently facing a deep energy transition (Chevalier et al., 2013). However, energy choices in France are now strongly bonded to the ones of other European countries due to the construction of EU27 and their common objectives regarding political and economic matters, especially regarding energy and environment. The future evolution of the French energy market can thus not be dissociated with the one of Europea. In this section, we track down the origins of European common goals on energy matters and analyse whether or not the European electricity market can be considered as one common market.

European initiatives for common energy market and common climate change mitigation measures stem from the political construction of European Union that started after World War II. The first European Community was the European Coal and Steel Community (ECSC) created in 1951 in order to facilitate energy supply. With the Treaty of Rome in 1957, European construction was reinforced with the creation of European Economic Community and Euratom (Community for Nuclear Energy). The creation of such communities showed the need for exchanges and economic solidarity within European countries in times of post-war reconstruction and then high growth. In

February 1986, the Single European Act properly states the will to create a unique market inside the European Union. In December 1996, the Directive on common rules for the internal market in electricity (European Comission, 1996) details the application to electricity market and marks the beginning of the formal process of market integration for electricity at the EU level. The European Commission lets each Member State choose its tools to achieve liberalization: it is „non harmonized liberalization“. The tasks to be completed are to open the market to new entrants, to stop controlling prices, and to create an independent regulator for each activity of the sector that can include competition(Grand and Veyrenc, 2011). One of the major decisions of this policy is to split many utilities into two parts: production and grid (it is called "unbundling"). Given the heterogeneity of institutions, markets, industries in European countries, and given the flexibility of European Commission Directives, the results are quite heterogeneous and the consequences not quite the expected ones (Percebois, 2013). In parallel, the above-mentioned European initiatives for climate and energy: EU Climate Energy Package and EU Emission Trading Scheme also impact energy policy in European countries. However, despite the strong commitment of the EU to achieve an internal market and to meet climate change mitigation objectives, there is no common energy policy, which may send mixed signals to countries torn between European objectives and national strategy in the matter.

As a conclusion, on the one hand, the political construction of Europe and common objectives regarding several energy issues thus allows considering the European market as a whole. On the other hand, the lack of common energy policy still makes it necessary to single out each Member State and study their particular energy policy. Major differences in energy policies are indeed to be noted from one country to another, especially regarding nuclear policies (e.g. France vs Germany). However, this 'energy divorce' could also be seen as a way to provide complementary approach to the management of a European generation mix (Chevalier et al., 2012).

1.5 Climate change mitigation issue and energy policies

We saw that the only common incentive in European Union is a carbon emissions reduction tool, which shows the major importance taken by the climate change issue. However, European climate policy cannot be dissociated from international climate policy initiatives, since climate change is technically a globalized issue. This section reminds the major effects of climate change on the environment and main prospects for climate change mitigation policies in the international and European scope.

1.5.1 The climate change issue: global impacts on the environment

The last IPCC report (IPCC, 2013) confirmed that many of the observed changes since the 1950s in the climate system are unprecedented over decades to millennia and are anthropogenic. The atmosphere and the ocean have warmed: 1983–2012 in the Northern Hemisphere was likely the warmest 30-year period of the last 1400 years. Global average surface temperature change for the end of the 21st century is highly likely to exceed 2°C and warming will continue beyond 2100 under most scenarios, although not uniform whether in time or space. Ocean warming accounts for more than 90% of the energy accumulated between 1971 and 2010. During the 21st century, it will continue to warm; heat will penetrate from the surface to the deep ocean and affect ocean circulation. The amounts of snow and ice have diminished over the last two decades: in the Greenland, in the Antarctic, in all glaciers worldwide, in the Arctic sea and in the Northern Hemisphere. The Arctic sea ice cover is likely to continue shrinking and thinning and the Northern Hemisphere spring snow cover to decrease during the 21st century as well as global glacier volume. Sea level has risen: the rate of sea level rise since the mid-19th century was larger than the mean rate during the previous two millennia. Global mean sea level will continue to rise during the 21st century. Under all scenarios, the rate of sea level rise will very likely exceed that observed during 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets. The concentrations of greenhouse gases: carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. CO_2 concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification. Climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO2 in the atmosphere. Further uptake of carbon by the ocean will increase ocean acidification. In the end, cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO_2 that will affect global economy.

1.5.2 Climate change and climate change mitigation measures: global impacts on economy and energy sector

According to the Stern Review (Stern, 2007, 2006), without action, the economic impact of climate change would be equivalent to losing 5 to 20% of global gross domestic product (GDP) each year, from now on. Impacts of climate change are assessed to affect water resources, food production and health: 'One-sixth of the world's population is "threatened" by water scarcities; 1 in 20 people may be displaced by a rising sea level; mortality may increase from vector-borne diseases and from malnutrition linked to income losses'(Stern, 2007). On the other hand, that limiting GHG emissions to 550 ppm would cost only 1% of annual GDP thanks to appropriate policy design. The main conclusion is thus that the benefits of early action far outweigh the costs of not acting. This conclusion is confirmed by many models, as in the AMPERE modeling comparison project that gives an assessment of Copenhagen pledges from 2010 to 2100 following different pathways for a 450 ppm GHG emissions objective (Riahi et al., n.d.). The comparison of nine models using different approaches (general equilibrium, partial equilibrium, dynamic recursive, perfect foresight, systems engineering) unanimously shows that the low ambition pathway for GHG emissions between 2010 and 2030 would make mitigation costs 30% higher for the whole 2010-2100 period compared to the high ambition pathway, and 50% higher in the 2030-2100 period.

The concern for such early action has indeed been vivid for more than a decade now since international action was first undertaken with the Kyoto Protocol in 1997, followed by a new negotiation at the Copenhagen summit of the United Nations[8] in 2009. In Europe, two initiatives have been launched: the European Union Emissions Trading Scheme (EU ETS) for carbon emission reduction (European Commission, 2003) and the EU Energy-Climate Package (European Commission, 2009a, 2009b, 2009c).

The EU Emissions Trading System (ETS) was launched to satisfy the Kyoto objectives; it covers the 27 EU member countries plus Norway, Iceland and Liechtenstein: it is currently the world's largest emissions trading scheme according to the World Energy Outlook, (IEA, 2012b). Other countries have introduced carbon taxes, some of them even combining both tools such as the United Kingdom. It was first designed to be applied within the 2008-2012 period, and submitted to new objectives for 2020 as a part of the EU Energy-Climate Package.

The objectives of the EU Energy-Climate Package for 2020 are known as the "20-20-20" targets:

[8] The summit takes place every year in a different country.

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

(Da Costa et al., 2009)

Future carbon prices are thus not fixed and depend of efficiency of the EU ETS for the 2012-2020 period. WEO assesses that average carbon price in Europe should increase to €23/ton[9] in 2020 and €31/ton[10] in 2035 if current policies were to be continued, while it could rise up to €98/ton[11] in 2035 in order to achieve the 450 ppm objective (New Policies and 450 Scenarios, (IEA, 2013). Among the literature, such prices correspond to 'soft landing' scenarios as in the ACROPOLIS comparison project including six models with various approaches (general equilibrium, optimization, simulation, integrated assessment), in which carbon prices range from €43/ton to €81/ton in 2020 and from €34/ton to €115/ton in 2040[12]. However such prices are highly dependent on international cooperation agreements and distribution of objectives between developed and developing countries. For instance achieving the 450ppm objective with an 80% emission reduction of EU27 by 2050 could lead to carbon prices up to €700/ton in Europe (Markandya et al., 2014).

[9] $30/ton, used conversion rate 1 USD2011 = 0,781 €2011 (INSEE)
[10] $40/ton, idem
[11] $125/ton, idem
[12] Converted to €2011 from €1995, used convesion rate 1 €11995 = 1,29 €2011 (INSEE)

2 Problem setting

The purpose of this thesis is to assess the conditions that would allow the penetration of SFR technology on the local market, that is to say, French and European market, within 2040, since it is supposed to be ready for industrial deployment by then. Despite its attractiveness, the context may be unfavorable due to the many factors mentioned in previous sections: competition with other power generating technologies, uncertainties on prices and sector organization brought by liberalization, climate and energy policy choices. The changes in the generation mix and the potential integration of SFR in this mix from 2040 depend on all these factors. As is will be developed thoroughly in Chapter 1, economic theory usually models investment choice with a long-term economic rationality approach based on assessment of costs, or costs and future benefits. However, observation of actual power generation mix in different countries highlights a large disparity in technology repartition in the mix that cannot be explained by this economic rationality approach. This is why we have chosen to focus on investors, i.e. power generation companies, and to analyze their behavior regarding investments in generation capacities taking into account all technologies - coal, gas, hydropower, wind, solar - and not specifically nuclear. The goal is to take an investor's perspective when it comes to renew or extend installed capacity, and to understand what makes him choose a technology or a portfolio of technologies over another one.

This dissertation therefore examines two research issues:

1) What are the drivers for investors' decisions on the European electricity market regarding investments in power generation capacities?

2) How do they affect the development of the European generation mix and the integration of FR in this mix?

We thus choose to focus on the local market and on major electricity producers: France, Germany, the United Kingdom, Spain and Italy, for they represent 65% of European Union (EU27) power generation (Grand and Veyrenc, 2011). This scope includes nuclear and non-nuclear or anti-nuclear countries (Italy, Germany), although the purpose is to assess SFR integration on the European market. Such a choice may seem paradoxical, but in reality, it is the most relevant one to answer our research questions, since it reflects European trends in electricity investment in both pro and anti-nuclear case and allows seeing all viable alternatives at stake. Moreover, these five countries are historically the heart of European Construction and significant example and lead for the rest of the Union.

Time horizon is 2040, the expected date for industrial deployment of FR. Since we aim to cast light on the future according to today's most certain data, the panel of technologies considers those most commonly used on an industrial scale: gas, coal, nuclear, hydropower, solar and wind. We thus do not consider technologies that are not yet quite developed such as biomass, geothermal energy, carbon capture and storage, and small modular reactors (SMR) in the nuclear field.

3 Methodologies: a multidisciplinary approach

To answer these questions, it is necessary to study the mechanisms at stake in the power generator's investment decision process when it comes to renew or extend installed capacity. A multidisciplinary approach has thus been adopted to provide complementary insights on the investigated issue.

Theoretical and historical analysis: drivers' sensitivity to historical context

A theoretical and historical analysis of investment decision in electricity capacities in Europe is made from 1945 to the present day. There are several purposes to such an analysis. The first one is to establish a review of the economic theories in the field of electricity investment choices. The second is to compare these successively dominant economic theories for a micro-economic vision of investment choices (Averch and Johnson, 1962; Baumol, 1977; Boiteux, 1971; Laffont and Tirole, 1993; Massé, 1953) with the history of the European electricity markets (post-war reconstruction, oil shocks, political construction of European market). Such a confrontation shows that the actual choices of European countries were not uniform either consistent with economic theories. The historical analysis thus allows identifying past drivers for investment decisions in the capacities of electricity production and understanding how these drivers have evolved over time in the specific context of Europe facing conflicts, technological progress and strong political developments. Such an analysis is necessary to take a step back on the issue under study and avoid certain bias, such as taking present drivers as everlasting.

Structural analysis and strategic foresight: building of scenarios

In the continuity of theoretical and historical analysis of drivers, a more detailed investigation of present drivers is needed to build scenarios for future generation mix evolution. In the economic literature, energy investments and mix evolution scenarios are usually addressed as driven by long-term economic rationality and solved by demand-supply equilibrium models: general equilibrium like GEMINI (Bernard and Vielle, 2008; Labriet et al., n.d.) or partial equilibrium models such as POLES (Criqui and Mima, 2012; Mima and Criqui, 2009), and WEO's model WEM (IEA, 2013). Choice of technology mix is determined by cost minimization, or profit optimization when prices forecasts are available and taking into account policies as constraint. However, since the historical analysis has shown that actual drivers for investment choices are different from the ones in the economic theory, we thus seek to identify the actual drivers for investment behavior and build scenarios according to these. This research problem thus has two steps:

- Identifying the drivers for investors' decisions;
- Analyzing their effects on future changes: elaboration of scenarios illustrating future trends in a descriptive and exploratory approach (in opposition to normative: there are no fixed objectives).

Literature review on scenario building shows that such an approach clearly belongs to the field of strategic foresight, in opposition to other scenario-building techniques: forecasting or fictional futures (Bland and Westlake, 2013). Among strategic foresight manuals and literature, structural analysis using the MICMAC tool is one way of identifying all the drivers for a system especially those determining its development (Coates et al., 2010; Durance and Godet, 2010; Hughes et al., 2013). This method focuses on clarifying the data of the problem, which is consistent with the purpose of our study.

Scenario quantifying based on systemic analysis with Design Structure Matrix and Quality Function Development Matrix

In order to give quantified assessment of electricity investment in the identified scenario, a tool is needed to replicate investors' choices. Going further than structural analysis, a systemic analysis is conducted, leading the development of a tool based on Design Structure Matrix and Quality Function Development Matrix methods. This tool uses the identified drivers to assess the compatibility of an investor (i.e. a power generating company) with a technology. Technology choices are thus modeled for the companies in the scope under study and in the three scenarios retained by structural analysis.

Focus on nuclear technologies: relative competitiveness of Generations III and IV through option value

As a last step of our research, we want to complete our research by analysing investment choices one step ahead of the investment choice in a power plant: investment choice in a research program. We narrow down our research to the French case, where a Fast Reactor research program is on the run, and try to assess the economic value of this research program. From an economic point of view, what does the SFR option bring to the French power generator? As said above, Generation IV Fast Reactors make better use of natural uranium than Generation III Reactors. They thus offer a valuable alternative in case of uranium shortage, but how much valuable? They are likely to have higher investment costs, so their competitiveness compared to the previous generation is not guaranteed. This step aims at assessing future costs of nuclear fleet in both cases: with the SFR option (i.e. with the research option), and without. We developed a model based on the real options theory (Arrow and Fischer, 1974; Bancel and Richard, 1995; C. Henry, 1974; Claude Henry, 1974) that compares the consequences of the two possible outcomes.

4 Structure of the work

In order to structure the thesis dissertation as clearly as possible, we have chosen to present our research in four chapters. A theoretical and historical analysis of investment decision in electricity capacities in Europe is first made, comparing the successively dominant economic theories in this field with the history of the European electricity markets (Chapter 1). The two following chapters present the works on scenarios for generation mix evolution. First, a detailed investigation and analysis of investment drivers is conducted with structural analysis; relevant scenarios are built according to the most important drivers identified (Chapter 2). These scenarios are then developed and quantified through the building of the investment choice tool applied to the cases of European power companies (Chapter 3). Last, the research works goes further in the investment decision problem by addressing the step prior to the investment in power generation facility: the investment in a research program for an electricity technology. An analysis on investment choice for the French research program on Generation IV Fast Reactors is made through real options model (Chapter 4).

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Chapter 1: Theoretical and historical analysis of Investment Decisions on the European Electricity Market

A preliminary version of this paper was presented at the 10th International Conference on the European Energy Market (Stokholm, Sweden) in May 2013 and published in the proceedings under the title 'Historical and theoretical approach of European Market: how does electricity investment evolve with historical context?'(B. Shoai Tehrani, D. Attias, J.-G. Devezeaux de Lavergne). It was also submitted to the review 'Energy Studies Review' in December 2013 under the title 'An Analysis of the Investment Decisions on the European Electricity Markets, over the 1945-2013 Period' (B. Shoai Tehrani, P. Da Costa).

This chapter constitutes the first step in our study of investment in electricity generation capacities in Europe. It addresses the issue from 1945 to the present day through an approach both theoretical and historical. Over this period, the drivers for investment decisions have indeed evolved in the context of Europe facing conflicts, scientific and technological progress, and strong political and academic developments. Moreover, electricity investment is today subject to new mutations, due to the still ongoing process of European market liberalization and the recent breakthrough of climate change issue, the latter imposing to reduce greenhouse gases (GHG) emissions, in particular through planned integration of renewables in the generation mix.

The purpose of the chapter is thus to compare the economic theories of the time to the actual decisions that were made, in order to shed light on the differences between the rational behavior described by theory and the actual behaviors of companies and governments. Of course, the generation mix of a state is, in the end, determined by the investment decisions of electricity companies. However, these decisions are influenced by many exogenous factors and follow drivers that are very different according to historical and geographical context. The research questions we seek to answer in this chapter are the following ones:

What were the main drivers for investors' decisions on European electricity markets? How did they evolve with time? What are the results of the liberalization process? What are the new stakes regarding regulation? How would they influence the liberalization process itself?

As a result, two main historical periods single out and structure the chapter:

- The 1945-1986 period (Section 1), during which national generation mix get formed in European countries, according to considerations often in contradiction with one another such as economic optimization, priviledging local resources, Ramsey-Boiteux rule, etc.;
- The 1986-2013 period (Section 2), marked by important mutations: the objective of liberalizing the electricity sector ending up in different degrees of competition in EU countries; new climate stakes and recent development of renewables.

1 1945-1986, from European reconstruction to oil shocks: a crucial period for the constitution of current power generation mix

1.1 Post-war electricity sector management: increased state control over power companies

In a post-war context, the first goal of European countries is reconstruction. For the electricity sector, the priority is thus to go back to previous levels of generation as soon as possible. In order to do so, governments take measures that end up with giving them an increased control on the electricity sector.

In France, from 1946 to 1951, investment is an emergency since there are numerous power cuts. Moreover, the currency's value experiences such volatility that it is difficult to get any relevant economic insight about investment decision. The main criterion is thus the amount of electricity that can be generated. In 1951 though, when the generation is back to the level it had before war and that there are no longer power cuts in the country, investments are slowed down and rationalized: the decision maker which is the French State, wants to minimize costs. Nationalization of power company is voted in 1946, which leads to the creation of *Electricité de France* (EDF) (Beltran and Bungener, 1987). In the United Kingdom, nationalization is also decided according to the *Electricity Act* voted in 1947. The *British Energy Authority* is created in 1948 and becomes *Central Electricity Generating Board* (CEGB) in 1957 (Grand and Veyrenc, 2011). Italy also chooses to nationalize the electricity sector in the Constitution in 1946, but national operator *Enel* is created only in 1962 (Grand and Veyrenc, 2011) due to industrial reluctance in the sector: nationalization indeed means that *Enel* has to absorb the 1270 historical power operators. The processus will be completed in 1995 (*Enel website*). In these three countries, the electricity sector has thus become a state monopole. Governments have direct control over tarification and technology choices.

The situation in Germany and Spain is different: they do not create state monopolies nor centralized planning (Grand and Veyrenc, 2011; Ibeas Cubillo, 2011). Their electricity industry corresponds to an integrated model. The German electricity sector keeps its structure including local and regional companies, due to the particular structure of federal German state itself – being divided in powerful *Länder*. Yet the sector is very integrated on both vertical and horizontal scales through numerous exclusivity contracts between power generators and grids, generators and distributors, but also from generator to generator. In the end the electricity sector in Germany is not submitted to competition and prices are controlled indirectly by the 1935 Energy Act. Technology choices are adopted at a federal level. In Spain, electricity sector integration happens through the coordination of private companies by themselves (Ibeas Cubillo, 2011). In 1944, 18 electricity companies create the *Asociación Española de l'Industria Electrica (UNESA),* in order to promote a real national electricity grid by developing more interconnections to ensure better supply (Asociasion espanola de la industria Electrica, 2013). Like in Germany, the Spanish government controls prices indirectly through the *Unified limited rates system* established in 1951 that sets maximum prices and regular tariff harmonization in the differents areas of the country.

European states thus take control of the power industry either through a monopoly called "natural monopole" by economic theory, either through an integrated model where potential entrants and prices are influenced by the state.

1.2 Cost-Benefit Analysis: the dominant economic theory over the period

In the aftermath of World War II, the Cost-Benefit Analysis is the dominant theory regarding electricity investment all over Europe. It justifies and supports the settling of monopoles and integrated markets. This theory was issued by works of *marginalist* economists and stems from the Welfare Economics founded in the 1930s and 1940s by Allais (1943), Hicks (1939), Pigou (1924), and Samuelson (1943): this branch of economics aims a assessing well-being with microeconomic techniques, by considering different alternatives of resources and revenue allocation. In the 1950s, the Cost-Benefit Analysis is initiated in France and other European countries by Massé (1953) and Boiteux (1956). This analysis implies assessing in an explicit way the total expected costs and total expected benefits for one or several projects, in order to determine which one is the best or the most profitable. Concretely, the application of these theories to electricity investment starts off with demand analysis: it is assessed to grow by around 7% per year. Technically, electricity supply at the time relies on two technologies: hydroelectric plants and thermal plants (Massé, 1953). Debates on the profitability of both types of technologies lead to define what a complete economic assessment of one technology's costs, which includes taking into account the whole lifetime of the facility, choosing the right discount rate, but also the ability of the fleet to supply the peak with the minimum of back-up capacity. In the end, the data of the problem are: the total production per year, the need of power of peak, and the total affordable investment. The first optimization model is built in 1955: according P. Massé, the electricity industry has found a purely objective tool to make investment decisions without personal bias (Beltran and Bungener, 1987).

Power generation is per se capital-intensive due to grid and plant investments that are needed. This is why Cost-Benefit Analysis comes along with integrated markets or monopoles, the latters being called '*natural*' according to the *Ramsey-Boiteux rule*. This rule demonstrates that a company with initial fixed costs (as in the electricity sector) undergoes losses if its price is equal to marginal cost (perfect competition); whereas in a natural monopole, it can reach equilibrium thanks to second order pricing superior to marginal cost and inversely proportional to demand elasticity (Boiteux, 1956).

1.3 The lack of risk and uncertainty assessment in Cost-Benefit analysis

In Massé's works for optimal electricity investment determination, the main risks at stake are discussed. It is yet clear that they are not enough integrated in the modelling or only in a very limited way (Massé, 1953) :

The risks related to operational costs and especially fuel costs were assessed by using past data: no changes in future trends were considered;

The risks related to investment costs were mainly due to construction risks associated with the land on which the plant was being built: it was considered as a mathematical expectation that was added to the investment cost as a security expense;

The risks related to financing programmes (volatility of public decisions) were identified but not taken into account;

The risks related to the expenses of financial compensation offered due to damages caused by plant construction gave us a first glimpse of the internalisation of externalities, but again no modelling was considered since it was too risky to be assessed.

In 1956 occurs the Suez crisis: the conflict occurred between Egypt and an alliance formed by Israël, France and the United Kingdom, after the nationalization of the Suez Canal by Egypt, the canal being a strategic step for oil imports. At this moment the first lacks of Cost-Benefit balaysis are clearly identified (Chick, 2007): exogenous risks like supply risk on imported oil like in the Suez crisis and its cascading effects are not correctly anticipated in this theory (Denant-Boèmont and Raux 1998; Massé 1953).

Economic theories on risk are nevertheless developed at the same time. In the 1940s and 1959s, Neumann and Morgenstern (1944) and Friedman and Savage (1948) address the issue of *decision maker's rationality when confronted to the risks at stake.* Weisbrod, Arrow et Henry completed these theories in the 1960s and 1970s by addressing the issue of public decision in uncertain environment: (Arrow, 1965) seeking to define optimal risk-sharing; (Claude Henry, 1974) discussing irreversible decision vs option value; (Weisbrod, 1964) showing that when individual-consumption goods cannot be provided profitably by private enterprise, it may serve the social welfare to subsidize their production. This progress is however exluded from marginalist modelling for electricity investment.

1.4 The initial competition between oil and coal

Oil and coal are the two main resources at the time for thermal power plants. European coal producers feeling threatened quickly demand protection against foreign oil imports. They argue that high risk resides in the political instability of Middle East, jeopardising supply, transportation and prices altogether. Did domestic coal producers get any protection in the 1950s and 1960s from cheap foreign oil imports?

In France, EDF had no obligation to use more coal than needed. It was easy given that France had few resources in coal compared to Germany and UK. Indeed, in the 1950s and 1960s, coal production reached 100 million tons in Germany (133 million in 1957) and 200 million tons in UK (197 million in 1960), whereas France's maximum production reached 59 million tons in 1958 and could never ensure selfsufficiency ((National Coal Mining Museum, n.d.; Office statistique des Communautés européennes, n.d.)). Moreover, marginalist economists (who did not take into account the supply risk) recommended reducing coal production in France and increase oil imports.

Contrary to France, United Kingdom and Germany, who had relatively important resources in coal, took measures to protect domestic coal production. In the UK, the government created a tax on oil imports in 1962, banned Russian oil and American coal imports, and from 1963-1964, imposed quantified coal use targets to CEGB (Chick, 2007). In Germany, such measures will occur later, after the oil shock, but are part of the same approach.

1.5 From *Peak oil* to developing alternative technologies to oil

After the two oil shocks in 1973 and 1979, a transitory period starts in Europe. In reaction to high oil prices, all countries take measures to reduce their dependency to black gold, including France that had not made this choice from the beginning.

A predictable effect of *peak oil* is the return to coal for some electricity producers. This happens mainly in Germany, where the Kohlpfennig is established in 1974: it is a tax on electricity consumption, used to support domestic coal. In 1977 the *Jahrhundertvertrag* (literally 'the contract of the century') makes it complulsory for power generators to get part of their supply from domestic coal producers.

The search for substitutes then develops, being very different from one country to the other. For instance, the United Kingdom quickly starts to explore the North Sea for new fossile resources, like gas, while France invests massively in civil nuclear energy.

Electro-nuclear program thus develop in France and Europe: their success or failure depend strongly on how national economies and companies resist to oil shocks, succeed in strategic and industrial nuclear deployment and manage public acceptance (or even public support).

In France, the high cash flows of EDF allow limiting the impact of high oil prices on consumers (Francony, 1979). EDF also manages to have low financial costs for the building of its nuclear fleet. For purely economic reasons, the choice is made to go with the American Pressurized Water Reactor (PWR) technology and buy the corresponding Westinghouse license in 1969 rather than French Graphite Gas Reactors developed by the French Commission for Atomic Energy (CEA). The French nuclear program (Plan Mesmer) is thus launched in 1974. The company initially intended to diversify the fleet by developing also Boiling Water Reactors (General Electric license) but gives up because of too high investment costs and significant difficulty in their agreement with the Swiss to build a power plant in Kaiseraugst.

The United Kingdom adopts the opposite approach. The nationally developed Advanced Gas Reactor (AGR) is chosen for the nuclear program (Grand and Veyrenc, 2011). However the program must then be abandoned in the middle of the 1980s for want of competitiveness. An alternative program based on the Westinghouse PWR technology is then launched in 1982 but will be abandoned again after the building of only one reactor in 1988 (*Sizewell B*) due to cuts in public budget and drifting costs.

In Germany, the technologies chosen by the companies are Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) developed loccaly by a *Siemens* subsidiary. Nuclear energy grows rapidly in Germany, although contested by the public from the start (which was not the case in France).

Between 1980 and 1986, Italy builds only four reactors and Spain five.

Besides, public acceptance of power generating technologies becomes more and more vital over the years. Local opposition for environment protection first focuses on coal, demanding that coal-fired plants were built outside cities. The phenomenon quickly reaches civil nuclear, in particular in Germany where the opposition to the building of a nuclear plant in Wyhl in the 1970s, successfully leading to abandoning the project in 1975, becomes an example for all anti-nuclear movements (Mills and Williams, 1986). Three Miles Island and Chernobyl accidents in 1979 and 1986 reinforce such movements all over Europe and United States.

The rejection of coal-fired plants by one part of European population is first addressed by the development of the first Combined Cycle Gas Turbine (CCGT) in the United Kingdom in 1991. This technology allows building smaller facilities than coal and nuclear plants, but still ensuring high profitability. It will also be favored by the end of the Cold War (in the late 1980s) since it means direct access to abundant and cheap Russian gas - indeed Russia is in 1990 the first gas producer worldwide with 629 billion m^3 ((Enerdata, n.d.)). Electricity producers using CCGT thus achieve competitiveness on the market thanks to accepted and moderate investment and thanks to cheap gas.

Such new entrants stimulate competition on the electricity markets until then integrated or monopolistic. However, the liberal mutation of Europe regarding electricity is more due to a combination of theoretical breakthroughs and political decisions.

2 1986-2013, from the process of European liberalization to climate change mitigation considerations: towards a mutation of electricity markets

2.1 Theoretical questioning of natural monopolies

In the aftermath of World War II, Cost-Benefis Analysis has shaped electricity investment choices in numerous European countries. It has stayed the major approach until the 1980s, although already theoretically contested in the 1960s. These works first question the efficiency of monopolistic and integrated model, and identify empirically their negative effects. First, a tendency to over-capitalize is revealed: since the tariff depends on invested capital, the firm will have interest in over-investing in order to increase their revenue – it is the Averch-Johnson effect (1962); the absence of competition also fails to encourage efficiency and triggers general organizational slack (Leibenstein, 1966). Besides, the relationship between the regulator and the electricity sector can lead him to protect the interests of the monopoly rather than the interest of consumers (Buchanan, 1975; Peltzman, 1976; Stiglitz, 1976): Buchanan pinpoints the limits of empowering an entity (such as the state) for the greater good, Peltzman the ones of regulation, and Sitglitz comparing resource extraction in a competitive market and in a monopolistic one.

This questioning goes further with Kahn, Baumol et Sharkey who address the issue of how to define a natural monopoly. (Kahn and Eads, 1971) reviews and questions the traditional definitions, while (Baumol, 1977) states that economies of scale are not a sufficient argument to justify a so–called "natural monopoly"; (Sharkey and Reid, 1983) proposes a new definition for the natural monopoly. According them, in a grid sector such as the electricity sector, natural monopoly does not apply to the whole sector but only to activities related to grid management. Competition can thus be introduced in other activites of the sector, such as production and distribution, for the benefit of consumers. This argument is the one later raised by EU and is at the root of the liberalization process in grid industries.

Last, in the 1990s, (Laffont and Tirole, 1993) emphasize these results by applying the principal-agent theory to regulation. They show that a monopolistic company has an asymmetrical relationship with the regulator: the company's interest is thus to take advantage of this situation regarding information on key points in order to increase their revenue.

2.2 The roots of the liberalization process: the political construction of Europe

With the political construction of EU initiated in the 1950s, several European Communities for trade and economy are created. These communities lead in 1986 to the Single European Act and in 1996 to the creation of a single European electricity market – or rather to the creation of such an objective – thanks to the EU Directive on *common rules for the internal market in electricity*.

The United Kingdom was a model for this market reform, since it was chronologically speaking the first European country to experience electricity market liberalization (Glachant, 2000).

The creation of an internal market in Europe has two goals. First, competition is expected to lower electricity prices for the consumers. Second, a European market allows to broaden the perimeter for resources in order to have better system optimization (Grand and Veyrenc, 2011). In practice, the reform allows member states to choose whatever measures they see fit to meet the objectives. They can either open the market to new entrants, either stop controlling prices, either create an independant regulator for every activity open to competition, etc. (Newbery, 1997; Perrot, 2002).

Given the heterogeneity of insitutions, markets and industries in differents European countries and given also the flexibility of European Commission Directives, results end up being very heterogenous.

This liberalization can first be assessed through the market concentration index: Herfindahl-Hirschman Index (HHI)[13]. Market concentration is often used to evaluate the degree of competition (we shall discuss this assertion later). Table 1 sums up the HHI of the five countries studied in this article. Indexes were calculated for year 2010 using Eurostat data and European power companies' annual reports (own calculus, cf Annex).

[13] The HHI index is the sum of the squares of market shares of N the companies present on the market:

$$H = \sum_{i=1}^{N} s_i^2$$

s_i represents the market share of the firm i in the market, and N the number of firms.The lower HHI is, the less the market is concentrated, and the higher HHI is, the more the market is concentrated.

Country	France	Germany	Italy	Spain	United Kingdom
HHI	7651	1354	943	1139	878

Table 1: HHI per country, own calculus.

Two groups are to be distinguished at first glance. On the one hand, France stands alone with a very high HHI equal to 7651, which indicates a very concentrated market. On the other hand, the four other contries under study have HHI between 878 and 1354 and reflect contrasted situations, from not concentrated (>1000) to concentrated markets (<1000).[14]

Today, the British market has an HHI of 878 and is thus acknowledged as competitive. This result can be explained by an institutional approach (Glachant, 2000) since, to achieve liberalization, some institutional configurations seem more favorable than others. This is why quick changes are easier to realize for very integrated companies or monopolies than for a group of several private decentralized companies. A state in which the government has a strong influence on legislation, rather than a federal state such as Germany, also is quicker to make decisions that will affect the whole country. Such an institutional combination is thus considered ideal and corresponds to the profile of United Kingdom: CEGB is a national integrated company, in an institutional environment staging a strong government.

It is though important to notice that HH Index has srong limits when it comes to describe a company's market power, since it does not take into account the different kinds of companies (private / public) nor the demand elasticity, neither the threat of potential substitute (Borenstein, Bushnell and Knittel, 1999). The electricity market thus has several characteristics that are not correctly represented by this concentration index. There are indeed different kinds of power generation companies (public service, natural monopolies, private companies, etc.) who are likely to

[14] Selon les lignes directrices de la Commission européenne sur la concurrence, un marché dans lequel le HHI est inférieur à 1000 est compétitif et peu concentré, alors que le marché dans lequel un HHI est supérieur à 2000 est très concentré et donc pas compétitif.

react differently in the same competition environment. Besides, electricity is a nessary commodity, but non-storable, with a pretty non-elastic demand obeying regular seasonal and hourly variations. Moreover, due to technical constraints, the ability of a producer to take a market share to another one is highly dependent on transmission facilities and existing grid, but also on base generation. HHI can also indicate the current repartition of power generation facilities in the company, but not the prices movements, neither que quality of delivered power.

2.3 The United Kingdom (HHI < 1000): a model for electricity sector liberalization?

The United Kingdom was historically the first country in Europe to deregulate its market from the mid-1980s, together with the United States of America on an international level. Today, we can take stock of the first results of this deregulation. The picture is a mixed one. Clearly, British deregulation has followed a specific process by starting from an integrated industry:

Sorting of power plants according to technologies: *British Energy* got in charge of nuclear power plants and *Centrica* of others. *British Energy* historically stayed into generation without engaging into downstream activities. The selling activity focused on a few big clients (companies), the rest of its generation being supplied through independent marketers;

Opening of the market to competition on different aspects of the value chain: generation and distribution;

Grid networks have a mixed regime: they are regulated but are allowed to be owned by actors of the competitive market.

What are the key constants to this day? The price of electricity is rather high compared on a European scale: 11.39 c€/kWh in UK against 7.71 c€/kWh in France (industry prices for 2013, Eurostat). Moreover, the electricity fleet is moving towards undersizing. It is now assessed that given the current pace of demand evolution and planned phasing out and building of power plants, the United Kingdom will not be able to meet domestic demand – the planned phase outs being more reliable than planned constructions (Energy UK, 2013).

What are the factors explaining the situation? − Let us first note that both factors are strongly correlated: when capacities decrease, prices should increase. Such prices can thus be explained by the relative decrease in supply capacities (compared to consumption). − Today, power generators have to face a volatile market in a country where the main fuel for power generation is gas - 46% of generation, inherited from the North Sea resources. Gas prices rose during this period and since electricity prices are strongly correlated to gas prices due to substitution effect, electricity prices followed. – An important volatility in prices came along with this rise. This volatility introduces important risks for wholesale electricity prices. Such uncertainty induces obvious risks for an investor regarding the decision to build new power plants. This risk affects the financing cost of new power plants, which is not always provided by wholesale market marginal cost pricing when it comes to peak capacities. The ability to cover investments thanks to market mechanisms thus seems limited: as a result, the market moves towards a reduction of installed capacity.

The issue of financing of new capacities is endemic to electricity market deregulation, since the required amounts for baseload power plants are high. One can reasonably assume that peak fuels volatility is not going to disappear. Besides, the British case also reminds that whereas the multiplication of supply sources is a *sine qua none* condition for competition, it does not automatically triggers the sink of prices. Today, competition is intense between distribution actors who buy electricity from the producers. If the margin of these distributors is with no doubt submitted to high pressure due to competition, it does not affect most of costs, since they depend on power plants and grids, the capacities of plants declining. Fares could decrease or at least be competitive on the Bristish market when supply will be sufficient in terms of available capacities and performing compared to other European countries (i.e. compared to prices obtained with average costs pricing).

Is it though a reason to refute electricity markets deregulation? The question often ignores one the key contribution of market liberalization: financing of new power plants and grids is not private and not public; which protects the taxpayer from unprofitable investments. As a counterpart, investors are more reluctant to finance the building of new power plants… Liberalization certainly needs to evolve in order to take into account the necessity of ensuring investments in new capacities. Today, the United Kingdom seems to have to intervene directly on the market to ensure the necessary electricity investments. The 2013 agreement between the British government and French company EDF for the building of two EPR is a strong example (Department of Energy & Climate Change and Prime Minister’s Office, 2013).

The liberalization of the Italian electricity market has also delivered visible results pretty quickly. The Italian state being favorable to liberalization from the start, it quickly auctioned part of the assets of historical oligopolies in order to favor new entrants. HHI of Italian electricity market is now 943. It is, with UK's HHI, the lowest among the considered countries. However, the importance of power company Enel on the Italian stage (28% of national generation) as well as the international stage shows that there is still a strong national champion; which is not the case in the UK. Electricity price in Italy reaches 11.22 c€/kWh in 2013 (same sources).

2.4 Germany (2000 > HHI > 1000): liberalized electricity?

The global attitude of Germany towards liberalization seemed favorable at first, but the process quickly introduced a reinforcement of state control over electricity operators, who were formerly used to auto-regulation. The market is still moderately concentrated with an HHI above 1000 and equal to 1354.

The current structure of the German electricity market is dominated by four companies: *E.On* and *RWE* ensuring 60% of generation[15] ; *Vattenfall* and *EnBW* 20%. The relative failure of electricity market liberalization in Germany can be partially attributed to German state's will to protect the volume of national electricity generation. The German electricity market has prices lower than the ones in UK, but higher than in France (8.6 c€/kWh in Germany vs 7.71c€/kWh in France). While Germany has abundant coal resources and coal is the cheapest fuel today, this higher price in Germany can be explained by strong penetration of renewables and high taxes on electricity prices.

Spain has adopted an attitude similar to Germany's: state control on prices, protection of historical operators (*Endesa* and *Iberdrola*) and strong support of renewables. HHI is equal to 1139 which describes a moderately concentrated market. Electricity prices reach 11.65 c€/kWh maingly for want of local resources.

[15] E.on and RWE are historically *multi-utilities* and are very present on the gas market as well as the electricity market.

2.5 France (HHI > 7000): an electricity market with no competition between actors but yet offering competitive prices

France is the country where liberalization was the less successful: there is one main operator regularly supported by French state policy in its application of European directives (the December 2010 NOME law, upon which we will come back later). French HHI is equal to 7651 which is very concentrated and makes France a rather special case in the European landscape. Of course, the fact that 75% of generation relies on nuclear can explain part of it. France thus avoided some of the mistakes of the integrated model. It did not protect coal in the 1960s when it was not competitive compared to oil, and chose in the 1970s the most profitable nuclear technology even though it was not the one developed nationally.

France is in a paradoxical situation: – *EDF* is a largely integrated quasi-monopoly but electricity is one of the cheapest in EU, which did not change over the last decade (Percebois and Wright, 2001; Percebois, 2013) – Under these conditions, one can legitimately question the opportunity to reform the French market and the need to break a monopoly ensuring more competitive prices than mupltiple actors in competition.

Two additional questions remain regarding the future of the French market. First, the *financing cost* of nuclear power plants (for addition or renewing of capacities): according to the two last CEOs of EDF, the current price of electricity does not allow financing of the fleet renewing. Second, is competition possible with a monopoly in possession of a rent (difference between marginal costs of nuclear and other generation technologies)? And if it is desirable, should an artifact be used to implement it?

In France, the situation is thus atypical in the European landscape, since EDF owns the quasi-totality of generation capacities and 100% of baseload capacities through its nuclear power plants. The NOME law tried to open the market to competitors by giving them regulated access to historical nuclear electricity (ARENH). In the end, the relatively high price fixed by the government for entrants to buy this electricity seems profitable to EDF.

2.6 New stakes in climate change and renewables: back to centralized policy for the electricity sector?

Environmental concerns growed the past decades with the creation of Intergovernmental Panel for Climate Change (IPPC) in 1988, the signature of the Kyoto Protocol in 1997, or the Stern Report (Stern, 2007, 2006). They leaded Europe to develop an ambitious plan for energy and climate: the Climat and Energy Package defined by the (European Commission, 2009a, 2009b, 2009d)[16]. New economic incentives can thus be expected to be put at use such as carbon tax or subsidies for research in renewables, in order to complete existing tools like the EU ETS (European Union Emission Trading System), and reinforcing the role of states in energy and electricity markets.

Regarding renewables, the need for investments coordination through new regulation is vivid in all European countries. The share of renewables is indeed growing in all generation mix over Europe, which raises several technical and economic issues (upon wich we will come back later). This new policy also includes societal issues. First, it will have to occur in spite of public's reluctance to more levies in time of crisis. The fact that such levies could be redeployed, though theoretically viable, has little chances to be heard from a political point of view. This new policy will also have to face the recent rise in coal use (and the associated GHG emissions) occurring in countries reducing the share of nuclear in their mix - mainly Germany.

From an economic point a view, it is difficult to find a unified theory allowing to determine optimal pricing and optimal investment amount when renewables are rising (OECD and Nuclear Energy Agency, 2012). This rise indeed makes theories on optimal investment faulty for two reasons. First, incentives such as carbon tax, feed-in tariffs or green certificates distort the data for traditionnel models based on cost minimization issue from Massé's works. Such models structure costs in fixed costs (investments) and variable costs (operation and maintenance, and fuel). *Ramsey-Boiteux* optimal pricing is based on marginal costs and determine investments from them. However, for unavoidable renewable energies, the variable cost is quasi-zero, so the marginal cost is also zero, which does not allow optimal pricing nor adequate price signal for investments. Besides, the fact that recent renewable technologies (wind, solar) are both unpredictable and intermittent are not yet correctly taken into account in existing models and are still under research. In reality, unpredictability and intermittence of renewable make it necessary to deploy demand response tools in order to compensate drops in generation like back-up gas-fired plants, and to develop interconnected grids

[16] It plans cutting greenhouse gas emission in 2020 (-20 % compared with 1990), increasing energy efficiency (+20 % more than *business-as-usual* projections for 2020) and objectives regarding the generation mix (20% renewable energies in the mix).

on larger distances to take advantage of the geographical dispersion of renewables. Such heavy investments are only starting to be negociated or deployed in a few areas of Europe (like Scandinavian countries). For instance, models taking into account these new aspects in electricity fleet modeling are being developed: model MAEL by (Dautremont and Colle, 2013), MIXOPTIM by (Bonin et al., 2013) or the one developed by (Bossmann et al., 2013).

3 Conclusion: towards restructuring of European generation mix?

We have conducted an analysis of drivers for electricity investments and of how these drivers have evolved over the six past decades. We thus have seen that a state's policy can follow standard economic theory like *Cost-Benefit Analysis*[17] of the one of *Natural Monopoles*, but mostly tends to be shaped by purely political and internal considerations.

Today, electricity investment have to be undertaken under the frame of electricity markets liberalization, which was triggered by new theories at the times (Averch and Johnson, 1962; Leibenstein, 1966); Buchanan, 1975; Peltzman, 1976; Stiglitz, 1976; Baumol, 1977; Kahn and Eads, 1971; Sharkey and Reid, 1983; Laffont and Tirole, 1993). The phenomenon of liberalization nevertheless bumps now into several hurdles. First, one has but to observe that electricity prices in Europe have not sinked but risen since the beginning of the process. Among the five countries under study, electricity prices for industry have on average grown from 6.31 c€/kWh in 2002 to 9.91 c€/kWh in 2013[18] (source: Eurostat). Critical situations in terms of electricity generation are also to be noted like in the United Kingdom. Besides, despite a liberalization process initiated more than twenty-five years ago, electricity markets can stay little competitive and very concentrated due to peculiar institutional reasons (Germany, France) that can as well stem from a certain economic rationality.

Last, the need to mitigate GHG emissions and to increase the share of renewable in the mix makes the intervention of states and EU necessary to set up new regulations regarding energy choices and investments. This *re-regulation* is nevertheless very different from the centralized driving

[17] For instance in France with nuclear investment: the choice was made of the most economically competitive technology even if is was a « foreign » technology (an American one).

[18] To be more accurate: from 6.14 to 11.39 c€/kWh in United Kingdom; from 5.62 to 7.71c€/kWh in France; from 6.85 to 8.60 c€/kWh in Germany; from 5.20 to 11.6 c€/kWh in Spain; from 7.76 to 11.22c€/kWh in Italy.

Europe used to know until the middle of the 1980s. Indeed, it does not question the foundations of liberalization, but still consists in pretty strong market control through fiscal tools.

We could not close this chapter without evoking one additional driver – the weight of which regarding investment decisions that should keep growing: the acceptance of electricity generation technologies by the European public, especially regarding nuclear power plants. Ever since the Fukushima accident in Japan in 2011 on March 11, and given the influence it has already had on some of the decisions of European countries, this parameter cannot be neglected anymore. Nuclear phase out in Germany, Italy, and Switzerland is all the more important that it can have unexpected but major politicial impacts on neighboring countries.

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5 Annex: HHI calculus

	Generation (TWh)	Market share
France	544,521	
EDF	476,3	87%
others		13%
HHI		**7651**
Germany	591,3	
EOn	105,9	18%
RWE	165,1	28%
EnWB	64,0	11%
Vattenfall	69,0	12%
others		32%
HHI		**1354**
Italy	290,7	
Enel	81,6	28%
EOn	13,9	5%
EDF	21,5	7%
Eni	25,6	9%
others		51%
HHI		**943**
Spain	292,0	
Endesa	67,0	23%
Iberdrola	58,2	20%
Gas Natural Fenosa	38,3	13%
EDP	16,2	6%
EOn	9,9	3%
others		58%
HHI		**1139**
United Kingdom	365,3	
Centrica/British Gas	32,9	9%
British Energy/EDF Energy	63,0	17%
Scottish Power/Iberdrola	27,9	8%
EOn	28,2	8%
Scottish and Southern Energy	46,0	13%
Npower	53,4	15%
others		58%
HHI		**877**

Table VII: HHI calculus with generation market shares. ***Source: Eurostat, 2010 generation data and power companies' annual reports***

	Capacity (GW)	Market share
France	127,9	
EDF	99,3	78%
others		22%
HHI		**6031**
Germany	167,9	
EOn	19,6	12%
RWE	31,4	19%
EnWB	13,4	8%
Vattenfall	14,0	8%
others		53%
HHI		**620**
Italy	115,3	
Enel	39,9	35%
EOn	6,1	5%
EDF	6,1	5%
Eni	5,3	5%
HHI		50%
		1273
Spain	103,9	
Endesa	23,1	22%
Iberdrola	19,7	19%
Gas Natural Fenosa	12,8	12%
EDP	6,1	6%
EOn	4,5	4%
		41%
HHI		**1058**
UK	89,1	
Centrica	6,0	7%
EDF Energy	13,0	15%
Iberdrola (Scottish Power)	7,1	8%
EOn	10,8	12%
Scottish and Southern Energy	11,3	13%
RWE (Npower)	11,5	13%
others		59%
HHI		**795**

Table VIII: HHI calculus with generation market shares. ***Source: Eurostat, 2011 installed capacity data and power companies' annual reports***

Chapter 2: Scenario Building based on Structural Analysis of Investment Drivers

Preliminary versions of this paper were presented at the International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13) in March 2013 in Paris, France, and published in the proceedings under the title '3 Investment scenarios for Generation IV fast reactors'(B. Shoai Tehrani, P. Da Costa); at the International Conference on Renewable Energies and Power (ICREPQ'13) in March 2013 in Bilbao, Spain and published in the proceedings under the title 'Investment scenarios in low carbon electricity in Europe'(B. Shoai Tehrani, P. Da Costa); at the 10th International Conference on the European Energy Market (EEM13) in May 2013 in Stockholm, Sweden, and published in the proceedings under the title '3 Investment scenarios for Generation IV fast reactors'(B. Shoai Tehrani, P. Da Costa).

It was also submitted to the review 'Energy Studies Review' in November 2013 under the title 'Three Investment Scenarios for Future Nuclear Reactors in Europe' (B. Shoai Tehrani, P. Da Costa).

This chapter aims at going further than the previous one by making a more detailed investigation of present drivers is needed to build scenarios for future generation mix evolution. In the economic literature, energy investments and mix evolution scenarios are usually addressed as driven by long-term economic rationality and solved by demand-supply equilibrium models. However, since the historical analysis has shown that actual drivers for investment choices are different from the ones in the economic theory, we thus seek to identify the actual drivers for investment behavior and build scenarios according to these. This research problem thus has two steps:

- Identifying the drivers for investors' decisions;
- Analyzing their effects on future changes: elaboration of scenarios illustrating future trends in a descriptive and exploratory approach (in opposition to normative: there are no fixed objectives).

The chapter is divided in three sections. Firstly, Section 1 provides a literature review describing the common academic approaches to electricity investments and explaining the choice of a strategic foresight methodology to answer our research questions. Secondly, the methodology itself – structural analysis – is presented and applied in Section 0. Based on both a literature review and interviews with experts, three key drivers are identified, with each driver being described by several variables and the interactions between analyzed and quantified. Thirdly, Section 3 describes scenarios for the future generation mix which are built on a couple of low/high assumptions for each driver. The interactions between variables are processed with the structural analysis software called MICMAC (Godet, 2008, 2001, 2000) in order to assess the relative importance of the different variables and rank the scenarios. Lastly, the most favorable scenarios for the penetration of Generation IV nuclear reactors are thus identified and then discussed in Subsection 3.4.

1 Literature review

1.1 Investment decisions in energy: short-term opportunities rather than long-term strategies?

In the economic literature, investment decision for energy facilities is addressed under both macroeconomic and microeconomic approaches. We here draw a brief summary of the most common methods used to describe energy investment decision.

1.1.1 How to determine investments: macroeconomic point of view

The macroeconomic point of view on energy investment matters is usually solved by demand-supply equilibrium models: general equilibrium or partial equilibrium models. Such models embracing a large scope of industrial sectors allow describing complex links between them and reflect the global economy with advanced accuracy. For the electricity sector, capacity investments are determined by demand evolution and existing power plants' lifetime. Choice of technology mix to meet the capacity requirement is then determined by merit order and cost optimization, or profit optimization when prices forecasts are available and taking into account policies as constraint.

We here give a few examples of the most famous models in the literature: GEMINI, POLES, and WEO's model WEM.

GEMINI-E3: General Equilibrium Model of International-National-Interaction for Economy-Energy-Environment (Russ et al, 2009)

GEMINI-E3 is a computable general equilibrium model. Its purpose is to evaluate welfare and distributional effects of various environmental policy scenarios. It thus describes the interactions between the economy, the energy system and the environment. The world version of GEMINI-E3 is divided in 18 regions, linked through endogenous bilateral trade. The exogenous variables of the model are government behaviour and policy. The outputs of the model are: projections of input-output tables, employment, capital flows, government revenues, household consumption, energy use, and atmospheric emissions. The model is global, but the sectors, the structural features of energy and environment and the policy instruments are disaggregated by regions. It can thus analyze the effects of policies for sectors, agents and regions, while the global economy remains in equilibrium.

In this model, the economic agents (firms, consumers) optimize their objective and determine the supply or demand of capital, energy, environment, labour and other goods. The demand of goods by the final consumers, the firms and the public sector constitutes the total domestic demand. On the supply side, investments are made to meet this demand. Investment choices in sectors and regions are made according to their respective profitability. Profit maximization thus is the driver for investment choice.

POLES: Prospective Outlook on Long-term Energy Systems (Russ et al, 2009, LEPI-EPE, 2006)

POLES is a partial equilibrium model for the development of energy scenarios until 2050. The model is based on yearly a recursive simulation process of energy demand and supply. It uses interconnected modules at the international, regional and national level. The main exogenous variables of the model are the gross domestic product and population for each country or region. Constraints such as greenhouse gas emissions or limited resources can also be added as exogenous variables. Costs and performance are described in technologically-detailed modules for the energy sector (oil, gas, power generation) and energy-intensive sectors (iron and steel, chemical sector, aluminium production…). Prices are determined endogenously based on oil price modeling: in the long term, oil prices depend on the scarcity of reserves; in the short run, they depend on spare production capacities of main producers.

As for power generation modeling, the supply side considers 26 electricity generation technologies, several of them being still marginal or under development, such as geothermal energy, fossil fuelled generation with carbon capture and storage or new nuclear designs. Price incentives such as feed-in tariffs can be included to project the development of new technologies. Demand is modeled through to typical daily load curves. The load curves are met by a generation mix given by a merit order based on marginal costs of operation, maintenance and annualized capital costs. Expected power demand over the year influences investment decisions for new capacity planning in the next step. In the end, investment decision is driven by generation cost minimization.

World Energy Model for World Energy Outlook (OECD/IEA, 2011)

The World Energy Model used for World Energy Outlook scenarios provides medium to long-term energy projections. This large-scale mathematical model aims at replicating how energy markets work through six modules: final energy demand; power generation; refinery and other transformation; fossil fuel supply; CO_2 emissions, and investment. The main exogenous variables of the models concern economic growth, demographics, international fossil fuel prices and technological developments.

Electricity investments are calculated in the power generation module (and then compiled with all investments in the investment module). The constraint is to meet the annual demand in terms of volume and peak in each region, and also to ensure security of supply in case of outages. The model determines how much new generation capacity is required annually in each region given several parameters: the existing capacity in each region; retirements of generation capacity during the year according to power plants lifetime assumptions for each technology; the change in peak demand compared to the previous year; and any building of renewable capacity decided by government policy. The model then makes its choice between different technology options on the basis of their regional long-run marginal costs (LRMCs). The LRMC of each technology is calculated as a sum of levelised capital costs, fixed operation and maintenance (O&M) costs, and variable operating costs. For nuclear though, additions of new capacity are subject to government policies and thus cannot be decided on the only criterion of LRMC. In this model also, investment decision is driven by generation cost minimization with two notable exceptions: nuclear investment and to a lesser extent renewable investment are political decisions.

1.1.2 How to determine investments: microeconomic point of view

From the microeconomic point of view, in this case the investor's point of view, the dominant economic theory for electricity investment choices has long been the Cost/Benefit analysis.

Cost/Benefit Analysis: investment choice driven by long-term economic rationality

As we saw in Chapter 1, the Cost/Benefit analysis is issued from the Welfare Economic theory founded in the 1930s and 1940s (Allais 1943; Hicks 1939; Pigou 1924; Samuelson 1943). This theory is diffused in France and other countries by Massé and Boiteux in the early fifties (Boiteux 1956; Massé 1953). However, it starts being questioned after the Suez crisis in 1956 (Chick 2007): works of economists show that the Costs/Benefits analysis does not properly include risks and in particular exogenous risks, like the risk on fuel supply (Denant-Boèmont and Raux 1998; Massé 1953). Von Neumann, Morgenstern and Savage in the 1940s and 1950s address the issues of the risk on decision makers' rationality (Friedman and Savage 1948; Neumann and Morgenstern 1944); Weisbrod, Arrow and Henry in the 1960s and 1970s complete these works by addressing the issue of public decisions in uncertain environment (Arrow 1965; Henry 1974; Weisbrod 1964). Henry in particular proposes to assess choices associated with uncertain outcomes through 'option value', by giving economic value to the future information and to the possibility of making future choices in less uncertain world (Henry 1974). Multicriteria analysis emerging around the 80s offers an alternative to Cost/Benefit Analysis by allowing taking into account non-monetary parameters more easily, but Cost/Benefit Analysis remains considered as the best tool to drive investment choices (Boiteux, 1994; Denant-Boèmont and Raux 1998).

In the end, the driver for investment decision is profit maximization or, in the absence of reliable assessment for future revenues, cost minimization, just like in the macroeconomic approaches. From a financial point of view, profit maximization can be assessed through many different methods: net present value, payback period, or return rate on investment (Bibas, 2011, Taverdet-Popiolek, 2010); still they are issued from the same theory.

Cost-benefit analysis is thus an efficient approach to introduce economic rationality into choices but is the appropriate tool to describe investment choices in a realistic manner? In crisis contexts like the Suez Crisis in 1956, or the oil crises in the 70s, many countries took immediate measures in favor of national security of supply, but these measures were not consistent with the long-term economic rationality promoted by the theory (Chick, 2007). Moreover, if investment choices had really been driven by Cost-Benefit Analysis all along, how come the power generation mix is so different from one country to another? Among the five countries under study: France, United Kingdom, Germany, Italy and Spain, striking differences are noted already. France relies on nuclear for 75% of national power generation; Germany on coal and lignite for 44%; and Italy on gas for 55% (Grand and Veyrenc, 2011).

1.1.3 Short-term opportunity decision making

Indeed, long-term economic rationality is neither the only driver, nor the main one for investment choices. Choices are made according to both of strategy and opportunity. This classic opposition between strategy and opportunity has led to a new trend (Chabaud and Messeghem, 2010) based on Venkataraman's work (Venkataraman, 1997). Given that a decision-making process is confronted with a context of complexity and the need for quick action, they argue that a decision often seizes an opportunity instead of being based on a long-term rational strategy. It is thus not the result of a precise analysis of all the parameters at stake, but of a more intuitive decision or an exploratory decision (Alvarez and Barney, 2007). Chabaud and Messeghem explain this side of decision-making as a way of optimizing resources by seizing opportunities. This interpretation is very consistent with the reactions observed after the oil crises in Europe. Many countries returned to using domestic coal, started new exploration for local resources or accelerated their nuclear programs, seizing every immediate opportunity to reduce energy dependence in the long term. Since long-term economic rationality is neither the only driver nor the main one for investment choices, we thus seek to identify the actual drivers for investment behavior.

1.2 Prospective approaches of energy: strategic foresight methods

Our research aims at studying investment choices beyond economic rationality and taking into account such behavior in the description of the investment process. As said in the introduction, there are two steps to our research problem:

- Identifying the drivers for investors' decisions;
- Analyzing their effects on future changes: elaboration of scenarios illustrating future trends in a descriptive and exploratory approach (in opposition to normative: there are no fixed objectives).

Such an approach clearly belongs to the field of strategic foresight, in opposition to other scenario-building techniques: forecasting or fictional futures (Bland and Westlake, 2013). For the first step, foresight methods usually recommend conducting interviews or a set of collective workshops. For the second, it is necessary to isolate the key variables influencing the system's development and to build the scenarios on these variables. Among strategic foresight manuals and literature, the works of Godet describe a full set of tools to practice strategic foresight from problem definition to scenario probabilities (Godet and Roubelat, 2000; Godet, 2008, 2002, 2001, 2000). Structural analysis using the MICMAC tool is one way of identifying all the drivers for a system especially those determining its development. This method focuses on clarifying the data of the problem, which is consistent with the purpose of our study.

Applications of these methods to the electricity and energy fields are numerous, addressing the issue of market liberalization as in work by(Bergman et al., 2006)), who built development scenarios for the business environment in the electricity industry, according to different assumptions of success of the European market reform in Finland. Another example is energy saving as described by (Wang et al., 2008) who apply these methods to the major barriers which prevent the practice of energy saving in China and the interactions among them. They can be used to assess low carbon scenarios in the UK and worldwide as shown in (Hughes and Strachan, 2010). (Schenk and Moll, 2007)) also use them for energy scenarios, showing that physical variables (e.g. amount of energy generation) rather than monetary indicators provide additional insights in scenario analysis.

The limits of Godet's methods are, however, described by Gonod, who identifies its subjectivity, its static character and the lack of uncertainty assessment as its main weaknesses, the two latters being a consequence of the former (Gonod and Gurtler, 2002). He proposes a different approach of foresight which is more dynamic and open to deep structural changes in the system under study (Gonod, 2006). Approaches similar to Godet's have thus been developed with a stronger focus on the collaborative aspects of foresight methods in order to lessen their subjectivity. (Hines and Bishop, 2006) insist on the bias of interviewed participants and establish a typology of participants' profiles (Laggards, True Believers, etc.) to identify common biases in such foresight approaches and separate them from relevant collected data. (Markard et al., 2009) also point out that scenarios neglect the co-development of technological and societal processes and that they lack the theoretical foundation explaining the interactions between the strategies of different players; they build a methodology that emphasizes the links between technological variables, player networks and institutional structures in order to identify plausible future innovation, in the case of biogas.

(Hughes et al., 2013) show that the level of uncertainty affects the relevance of low-carbon scenarios. They propose to reduce uncertainty by a player-based system with a more in-depth analysis of the interactions between them, thereby leading to better scenarios.

However, in a recent review of foresight methods (Coates et al., 2010) and reflections on the numerous uses of strategic foresight (Durance and Godet, 2010; Godet, 2010), the authors remind us that the validity of the analysis conducted with their tools is not only dependent on the tool's performance, but also on the user's rigorous approach and common sense. Bearing in mind the limits cited above and the existing bias, we chose Godet's structural analysis method to pursue this prospective study.

2 Framework of the Study: Structural Analysis

This section describes the structural analysis performed in an attempt to answers to our research questions within a rigorous methodological framework. Since we are interested in the investment decision of the power generating company, the system under study thus comprises the power generation company and the set of investing conditions with which it is confronted.

2.1 Retrospective analysis: generation mix and market liberalization in Europe

The first step of our analysis must look back on historical aspects in order to determine the constants in human behaviour and to get some perspective on the bias of our time: it is commonplace to say that 'History does not repeat itself, but human behaviour certainly does'. In the history of the European market, there are two main processes to be studied: 1) the constitution of the European generation mix from the fifties up to now in order to understand past investment choices, and 2) the European market liberalization that started in the nineties in order to understand the kind of context with which current investors are confronted.

This historical analysis shows that European countries have massively privileged local resources (such as coal in Germany) or the development of a locally well-mastered technology when local resources were poor (such as nuclear in France). This tendency was reinforced after the two oil crises in the seventies, leading European power companies to ensure the security of supply at high costs. The driver to these decisions was the state policy with the purpose to ensure energy independency.

After the oil-price slumps in the eighties, a market reform was implemented in Europe in the nineties to create a single European competitive market out of all the national markets in place, which were often integrated monopolistic markets (Grand and Veyrenc, 2011; Hansen et al., 2010). The reform was unequally applied in the different countries (to a great extent in the UK, which was a pioneer of liberalization and very little in France, where the natural monopoly model was considered a success within the rule of the Ramsey-Boiteux pricing (Baumol, 1977), leading to various market structures and concentrations represented very different environments for investors. The unification of the European market remains unachieved, mostly because of a lack of interconnections between countries (Grand and Veyrenc, 2011). Market structure is thus another driver for investors' decisions.

2.2 Drivers: from investment conditions and power companies

2.2.1 Investment conditions in electricity generation technologies

As for listing the variables, we conducted interviews of experts taking into account all the bias of such interviews, before exploiting this information and expanding on it with a close review of related literature. Sixteen experts who are known for their visions in their area were interviewed: 3 technology development experts in the nuclear field and 9 policy experts from a research institution (the CEA) and embassies (12 countries in Europe, North America and Asia), 4 economic experts from energy companies (EDF, Areva) and 1 independent consultant.

Our historical approach showed that drivers were state policy (energy independency and local employment), the local technology and the market structure.

As a result of these interviews and our literature study, we were able to distinguish three mains drivers that shape the investing conditions for power generation companies: 1) State policy driver; 2) Market driver; 3) Technical driver.

From a general point of view, the state's priorities are usually the security of supply and energy independency. However, there is no real electricity supply problem in the particular context of Europe: it is more the case in emerging countries such as China and India with high growth. The technological advancement of the country is a driver that goes hand in hand with demand satisfaction in emerging countries. In Europe, the energy policy is more about climate change, renewable energies and nuclear acceptance (reducing the use of fossil fuels points in the direction of energy independency). Today and within our European scope, the policy driver thus contains four dimensions:

- Climate policy, which is divided into two aspects: carbon policy and renewable policy;
- Carbon policy, which will determine the incentives regarding carbon emissions and promote low-carbon energies, which are at the heart of our study.

- Renewable policy, which is closely related to carbon policy, can be described in Europe by four kinds of tools: feed-in tariffs, green certificates, tenders and fiscal incentives (Bordier, 2008).
- Nuclear policy: the use of this energy can be controversial according to the national context, with the positions in the five countries investigated being very different. France has historically adopted a strongly pro-nuclear stance; the importance of the nuclear facilities and expertise inherited from the past should maintain France in a strong pro-nuclear stance. The UK has adopted a moderate pro-nuclear stance , although recent development in nuclear in the UK shows strong support, as the agreement with EDF for the Hinkley Point shows ((Department of Energy & Climate Change and Prime Minister's Office, 2013); however, the government's will never to directly support financially nuclear makes UK policy "moderately pro nuclear". On the other hand Germany, Italy and Spain have adopted an anti-nuclear position; for pro-nuclear countries, we add the "strike price" variable to describe the nuclear policy more accurately;
- Electricity market reform policy, which will have a direct influence on the investors' environment and the investors' profiles themselves. To elaborate our scenario, we included this driver in the second category: 'market driver'.
- The market driver contains several aspects:
- Level of concentration and competition of the market that can be characterized by the number of players present on the market and the Herfindahl–Hirschman Index (HHI[19]);
- Market policy led by the country, which will have an influence on both the market structure through market reform policy and market coordination, which is essential to investors' decisions.
- As a first approach, we have considered that the market reform policy is described by the choice whether to develop interconnections, and more generally, the electricity grid. The "market structure" driver has thus been considered under both angles of concentration and interconnections. As for market coordination, investment coordination is described by the different financing methods: corporate financing, project financing, hybrid method mixing the two latter, or other original financing methods (e.g., financing from the future customers) (IAEA, 2009; OECD, 2009).

[19] HHI definition, with s_i the market share of firm i in the market, and N the number of firms:

$$H = \sum_{i=1}^{N} s_i^2$$

The lower HHI is, the more the market is competitive, and the higher HHI is, the more the market is concentrated.

The technical driver (regarding coal, gas, nuclear, hydro, wind, solar) includes building and generation costs, as well as load factors that will directly impact the expected profits, but also all the parameters that will make the technology more or less easy to acquire for the investor, i.e. the construction timescale, the average size of the plant for this technology, and the technology complexity. Since the perception of technology complexity depends on every company according to its own expertise, we will not include it in this technical driver but in the drivers proper to the company.

The different decision variables corresponding to the three main drivers are listed in Table I.

N°	Variable	Related Driver
1	Carbon tax (€/tCO_2)	Policy Driver
2	CO_2 quota	
3	Feed-in tariffs for renewables (€/MWh)	
4	Green certificates for renewables	
5	Tenders for renewables	
6	Fiscal incentive for renewables	
7	Nuclear position	
8	Nuclear strike price (€/MWh)	
9	Stability of policy	
10	HHI concentration index	Market Driver
11	Development of grid and interconnections	
17	Corporate financing	
18	Project financing	
19	Hybdrid financing method (corporate and project financing)	
20	Other original financing method	
12	Construction costs (€/MW)	Technical Change Driver
13	Generation costs (€/MWh)	
14	Building period (year)	
15	Size of plant (MW)	
16	Load factor (%)	
21	Shareholding structure	Company driver
22	Market Capitalization	
23	Annual Production	
24	Generation Mix	
25	Market share	
26	Annual revenue	

Table I: Decision variables for each driver

2.2.2 Drivers from characteristics of companies

- In order to understand investment choices, it is relevant to compare investor profiles and technology investment conditions: for instance, capitalistic investments such as coal or nuclear plants are *a priori* achievable only for companies with sufficient revenue and capitalization to support the building costs, and low-capital cost technologies such as small renewable facilities are at the reach of all investors. Nonetheless, the thorough investigation of investment conditions shows that original financing methods such as conjoint investment from a consortium of power generation companies or financing from long-term electricity purchasers can broaden the scope of companies able to make capitalistic investments.

- The second step of our analysis thus consists in defining who the investors are and how their characteristics will influence their own investment decisions.
- Investor profiles can be analyzed through a few key characteristics that are:
- Shareholding structure, which will give an indication on the investment strategy of the company (private shareholders: institutional, public float, or state shareholders: state, ministry, local authority, and weight of the different types of shareholders);
- Market capitalization and annual revenue, which indicate the size of the company from a financial point of view and the size of the investments the company can support,
- Total annual production, that indicate the size of the company from an industrial point of view;
- Generation mix, which shows the company's fields of expertise;
- Market shares on markets where the company is active, which show the international scope of the company.

An overview of the companies falling within our scope shows that most of the current power generation companies are former historical operators who used to be in a dominant market position (Grand and Veyrenc, 2011). Their shareholders are state players such as the government, a ministry, or local communities, institutional investors such as banks and insurance companies, and private shareholders (public float), with the weight of each type of shareholder depending on the national position towards market reform and the specific history of the company. Their annual revenue and market capitalization represent several dozen billion euros and annual production of around a hundred TWh (EDF et al., 2012). Their dominant technologies are mostly coal and gas (and nuclear for EDF). Most of them have crossed the border of their initial market and have started being active on neighboring markets: e.g. EDF is present in the UK and Italy, and EOn in the UK, Italy and Spain. We can also observe concentrating movements between these companies: for instance, the Italian operator ENEL owns the Spanish Endesa, the French operator EDF owns British Energy, and the Spanish operator Iberdrola owns Scottish Power.

Yet another type of profile seems to be emerging with the market reform, the one of small power companies. Such companies are generally young, dating from the nineties or 2000 such as the wind operator Theolia or the solar operator Solaire Direct. Their shareholding structure boasts no state players; their revenue is around a few million euros and their annual production less than 1 TWh. They mostly specialize in one technology since their size does not allow them to diversify, mostly in recent technologies such as renewables or CCGT. They can be local or international operators, representing minor market shares in any case.

As mentioned above, national positions regarding the market reform differ from one country to another, which affects the development of power generation companies. France, Germany and Spain tend to protect their historical operators on their domestic markets and promote their international development thanks to the reform; the UK and Italy are really promoting competition on their own market, with Italy limiting market shares for the different players on the Italian market for instance. The development of investors profiles towards multinational concentrated companies or towards small power operators will depend on the changes to the global market structure in association with the market reform policies led in EU countries.

Shareholding structure	Company driver
Market Capitalization	
Annual Production	
Generation Mix	
Market share	
Annual revenue	

Table II: Company drivers

2.3 Analysis of interactions: matrix of direct influences and dependences

The MICMAC method consists in assessing the relative influence of all variables upon another[20] in order to fill a matrix called the Matrix of Direct Influences.

[20] For each variable, its influence on every other variable is quantified from 0 to 3, the value 0 corresponding to no influence at all, and 3 to a strong influence. The letter P is used when a potential influence is sensed, but

Information extracted from literature review and interviews allowed us to fill the Matrix of Direct Influences and Dependencies[21]. Since filling the Matrix by the experts would need a training session and a workshop in presence of all experts, the matrix was not given to them to be filled in but was filled in using a compilation of their answers and the results of the literature review as well.

	1 : Carbon tax	2 : CO2 quota	3 : Feed-in tariffs for renewables	4 : Green certificates	5 : Tenders for renewables	6 : Fiscal incentive for renewables	7 : Nuclear position	8 : Nuclear strike price	9 : Stability of policy	10 : HHI	11 : Development of grid	12 : Construction cost Euro/MW	13 : Generation cost Euro/MWh	14 : Building period	15 : Size of plant	16 : Load factor	17 : Corporate financing	18 : Project financing	19 : Hybdrid financing method	20 : Other original financing method	21 : Shareholding structure	22 : Market Capitalization	23 : Annual Production	24 : Generation Mix	25 : Market share	26 : Annual revenue
1 : Carbon tax	0	3	3	3	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	3	0	3
2 : CO2 quota	3	0	3	3	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	3	0	3
3 : Feed-in tariffs for renewables	3	3	0	3	3	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
4 : Green certificates	3	3	3	0	3	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
5 : Tenders for renewables	3	3	3	3	0	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
6 : Fiscal incentive for renewables	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
7 : Nuclear position	P	P	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	0
8 : Nuclear strike price	P	P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
9 : Stability of policy	3	3	3	3	3	3	3	3	0	0	3	0	0	0	0	0	1	1	1	1	3	0	0	3	0	0
10 : HHI	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 : Development of grid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
12 : Construction cost Euro/MW	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	3	0	2	0	0
13 : Generation cost Euro/MWh	3	3	3	3	3	3	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	3	3	3	0	3
14 : Building period	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 : Size of plant	0	0	0	0	0	0	0	0	0	0	2	3	0	3	0	0	3	3	3	3	0	0	3	3	3	0
16 : Load factor	0	0	3	3	3	3	0	0	0	0	3	0	0	0	3	0	0	0	0	0	0	0	3	3	0	0
17 : Corporate financing	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
18 : Project financing	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
19 : Hybdrid financing method	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
20 : Other original financing method	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
21 : Shareholding structure	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	3	3	3	0	3	0	3	0	0
22 : Market Capitalization	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3	0	3	3	3	3	3	0	0	0	0	0
23 : Annual Production	0	0	0	0	0	0	0	0	0	3	3	0	3	0	2	1	0	0	0	0	0	0	0	0	3	3
24 : Generation Mix	3	3	3	3	3	3	2	0	0	0	3	1	0	1	1	0	1	1	1	1	0	0	3	0	0	0
25 : Market share	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3	3	3	3	0	0	0	0	0	0
26 : Annual revenue	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	0	3	0	0	3	0

Table III: Matrix of direct influences

not clearly indentified. In the matrix of direct influences, each line contains the values attributed to the variable's influence on every variable in the column. Therefore the lines show how much influence the variables have on the other ones and the columns show how much the variables depend on the other ones.

[21] According to observations by Godet (2001), an optimal filling of the matrix corresponds to approximately 20%; our matrix has a filling rate of 27.8%, which is reasonably close.

The influence of a variable on another is considered direct if the value of the influencing variable appears in the definition of the influenced variable. For instance, Feed-in-Tariffs are designed according to technology generation costs, revenues of power generation companies are partly determined by incentives (Feed-in-Tariffs, fiscal incentives, carbon price or carbon tax). It is important to note that filling in the matrix is about identifying crossed influences between the variables in our list. It does not mean that the variables depend exclusively on other variables coming from the list. In the next paragraph, we detail how the matrix was filled in.

Policy drivers

Incentives for renewable and carbon are designed based on: the global policy of the country regarding this matter, which means that all climate policy incentives are influenced by one another and are influenced by the global stability of climate policy. The costs of technologies have a direct influence on shaping incentives (FiT, price of carbon, fiscal incentive, etc.) so that the incentive plays its role well. The technical characteristics affecting the production and thus revenue are also influential, i.e. the load factor (for renewables that face intermittency issues, not for carbon prices, which are intended so that the carbon costs for the company be proportional to its carbon emitting generation). Incentives are also shaped according to the existing mix in the country that the policy wants to change, i.e. the generation mix of all power generation companies. Since all these influence are direct and very obvious, they are assessed with the maximum value of 3.

Carbon incentives could be influenced by the country's nuclear stance, since a pro-nuclear stance can favor a low carbon policy: potential influence.

The nuclear stance is a long-term political decision that goes back to the 80s & 90s and the inertia of which is hardly likely to be influenced by other listed drivers. However, some drivers have a moderate or weak influence on it: sometimes it can be part of a low-carbon policy. It is influenced by the stability of policy (in the US, the possibility of a radical change in energy policy makes it impossible to have a strong pro-nuclear policy); the profile of shareholders from power generating companies may have more or less influence on the political opinion on nuclear since the presence of government entities in the shareholders supposes common interests or at least closer interaction between the state and the company. Moreover, the existing generation mix of companies' influences the state's nuclear stance, since the lifespan of power plants causes certain inertia. A national electricity mix relying on nuclear for 75% of the generation is less likely to switch to an anti-nuclear position than a mix with 20% nuclear share.

The nuclear strike price (the incentive identified) depends on the state's nuclear stance and the stability of its policy, as well as been designed according to the generation cost.

Policy stability influences many other drivers rather than depends on them, but no direct influence from the other drivers has been identified: in fact, it depends on many factors, some of them outside the scope under investigation, like the political context and organization of the country, and is mostly the result of indirect influences of others drivers.

Market drivers

The HHI depend on the market shares of the companies that can be calculated using the production or company size, which is why the corresponding indicators were also listed as influential on the HHI.

The development of grid depends on: the stability of policy since real perseverance is needed to establish new lines; the concentration of the market since the multiplication of players will make more interconnections necessary; the size of plants since it is an indicator of a centralized or decentralized market (smaller plants means more plants and therefore more interconnections); the load factors: low load factors means there is a need for more capacity and more interconnections.

The choice of a financing method is mostly influenced by the financial indicators of the size of the company: market capitalization, market share and annual revenue to a lesser extent. The choice is also influenced by:

- the shareholding structure of the company: the private or public profile of the company offers different kinds of financial guarantee and thus leads to different financing methods;
- the size of the project, which determines the total investment cost and building time, so the payback period;

- the existing mix, since it shows the company's field of expertise and can orientate the choice of financing method;
- policy incentives: supporting incentives, since they can offer financing structures (such as tenders) or financial security (feed-in tariffs/strike price, fiscal incentive, green certificates);
- carbon-related incentives, since they increase risk on profitability.

Let us mention that, of course, the cost of financing will depend on the generation cost, investment cost, all policy incentives including carbon incentives; but it is not the cost of financing that is examined here, it is the choice of the financing method.

Technical drivers

The MW construction cost can vary depending on the construction timescale since the longer it lasts, the higher the €/MW cost and the size of the plant, due to a potential scale of economies.

The MWh generation cost is influenced by the construction cost to the MW and the amount of generation (to evaluate variable costs). Of course, generation costs also depend on others parameters that were not identified as drivers per se: cost of fuel, cost of workforce, etc. (they are all included in the 'generation cost' driver).

The construction timescale mostly depends on the size of plant but also – to a lesser extent – on the existing mix of the generation companies, since it indicates their level of expertise in the different technologies

The load factor is mostly a technical parameter imposed by the technology: base technologies such as coal and nuclear are required to have an approximate load factor of 80%, while intermittent renewable technologies have an average load factor of 20-25%. However, according to variations in demand, this load factor can be changed: it is particularly true for peak technologies such as gas or hydro, but it can also affect base technologies. This is why the production of the company is assessed to have a weak influence on the load factor.

Company drivers

The shareholding structure can be mostly influenced by policy stability, which will keep the same company profile through time (public/private). It can also be influenced by the size of the capital, i.e. the market capitalization, since a large company is more likely to be a former state-owned company with still government entities among the shareholders, than a small company born with the liberalization process. Lastly, it can be influenced by the policies and incentives in general.

The market capitalization can be calculated by different methods. Since the calculation depends on shareholder expectations, it mostly depends on the shareholding structure of the company; and since it involves the company's profits in most methods, revenues and costs are considered highly influential. Financing choices are considered to influence costs so are listed to have a small influence. As said above, other costs such as fuel costs are influential but do not appear here since they are already included in generation costs.

The value of annual production of a company is above all conditioned by demand and its capacity. On a more detailed level, it depends on:

- the generation mix,
- the size of the plants and their load factors, since the plants will generate more or less electricity over the year according to their capacity and the type of technology (base, intermittent, peak);
- generation costs of the technologies;
- grid constraints;
- incentives for carbon emissions (to a lesser extent).

Positive incentives on renewables and nuclear are not considered influential since the renewable technologies considered here are intermittent and thus have priority to sell, and that nuclear is supposed to work on a base load. Since coal is also a base-load technology, this means that generation from gas could mostly be impacted.

The generation mix depends on the installed mix and how it can be used to respond to demand and thus is influenced by:

- the size of plants (they define the installed mix);
- the load factors of the technologies in the mix (since they give the actual generation of the installed capacity);

- generation costs (merit order);
- investment costs, thus involving size of plants and MW investment costs (since the necessity to make an investment profitable can condition the load factor);
- the incentives to use some technologies rather than others: support incentives for renewables or nuclear, or negative incentives for fossil technologies.

The market share of a power generation company is usually calculated in installed capacity or in generation (for instance to calculate the HHI indicators in European Commission reports); the traditional definition of market share is based on the company's revenue. The market share thus depends on the size of plants (installed capacity), the annual generation or the annual revenue (for the theoretical definition).

The annual revenue is influenced by the annual production and all the incentives affecting the revenue.

3 Results: Building Scenarios for Generation IV

3.1 Development assumptions for all drivers

In order to build investment scenarios based on these drivers, it is necessary to extract assumptions from our previous analysis regarding their development over the timescales of our study. Low and high assumptions for each dimension of the policy driver have been formulated.

We have identified a strong climate policy scenario and a moderate climate policy scenario that can be quantified by their carbon price ranges, with carbon pricing being the key tool of climate policy. Today EU ETS has had low carbon prices around a dozen US$/ton CO_2 for a few years. Strong climate policy would imply increasing this price, which could be achieved by the mean of a reform of the carbon market or a carbon tax. Given the European objectives of 3x20 carbon prices are expected to rise, the question is how much. The moderate climate policy would consist pursuing the EU ETS system with reforms, leading carbon pricing to increase from a dozen $/metric ton to $45/t$CO_2$ in 2040. A strong climate policy would increase the carbon price up to 120 $/t CO_2 in 2040 (IEA, 2012b). The renewable policy is closely related to the carbon policy, as the European Climate-Energy Package shows therefore a strong climate policy scenario corresponds to strong incentives both in terms of long-term support and high amounts, whereas the low assumption would correspond to current trends (Bordier, 2008). We assume that nuclear policies do not change within the considered period[22].

In theory the liberalization should lead the market to decentralize, which is far from being obvious in the case of European electricity market. We will describe concentration assumptions using the HHI: as in the European Commission Guidelines on competition, we consider a market in which the HHI is lower than 1000 as competitive and low concentrated, whereas a market in which the HHI is in excess of 2000 is highly concentrated. By observing the HHI of different European countries, we can see that some countries have managed to go under 1000 (UK, Italy), whereas others remain very concentrated (France's HHI is above 7000). Concentration movements since the beginning of the liberalization process are not in favor of a European deconcentration. For this reason we make both a high and a low concentration hypothesis.

A high concentration assumption goes along with a low development of interconnections; a low concentration market with a strong development of interconnections. Let us notice that development of interconnections is an issue due to systematic strong local opposition. As for the different financing methods, we consider the flexibility of choices in financing as a static decision variable and thus make no assumption regarding their potential development.

Among the technologies being studied, coal, gas, hydro and nuclear are considered to be time-tested and expect less progress than wind and solar[23]. The technical driver thus corresponds mostly to the expected technical change for these two recent renewable technologies, wind and solar. For this driver, we made a high technical change assumption and a low technical change assumption. The technical change would impact construction costs, generation costs and technical constraints of each technology: load factor, average size of plants, construction time; WEO 2011 scenarios allow us to estimate the expected cost reduction (IEA, 2012b). Since the impact on these different costs is quite homogenous according to the expected progress for one technology, overnight investment cost

[22] This assumption may be considered a limit in the elaboration of scenarios; nevertheless, such political stances commit long-term industrial behaviors and for this reason it is relevant to assume a certain degree of inertia in the pro- or anti-nuclear stance.

[23] It is true that nuclear technologies are still experiencing innovation, but even new generations of nuclear reactors (Generation III, Generation IV) are based on experienced concepts: pressurized water reactors for Generation III, which is one of the most current concepts in operation today, and sodium-cooled fast reactors for Generation IV, the technology of which was experienced in France in the eighties with the Phenix and Superphenix demonstrators, and is today in operation in Russia on a few reactors (BN-600, BN-800).

reduction is a relevant indicator: Table IV gives the orders of magnitude of investment cost reduction for the two assumptions, which shows that progress is mostly expected for solar technologies (PV and CSP).

Technology	Low technical change	High technical change
Onshore wind	10%	20%
Offshore wind	25%	50%
Solar PV (utility and rooftop)	50%	75%
Concentrated solar power	40%	90%

Table IV: Investment cost reduction between 2010 and 2040

Regarding the company drivers, the development in the size of companies naturally follows the assumptions on market concentrations and the HHI. However, since the aim of the study is to assess the reaction of companies to investing conditions and to observe how the development of their mix could be affected, no assumption is made on company drivers.

A total of 24 different scenarios are possible as a result of the number of assumptions:

- high and low assumptions for the climate policy driver, market driver, and technical change driver,
- high, low and medium assumptions for the nuclear policy.

Scenario 1a	strong climate policy	low technical change	concentrated	strong pro-nuclear
Scenario 1b	strong climate policy	low technical change	concentrated	moderate pro-nuclear
Scenario 1c	strong climate policy	low technical change	concentrated	anti-nuclear
Scenario 2a	strong climate policy	low technical change	not concentrated	strong pro-nuclear
Scenario 2b	strong climate policy	low technical change	not concentrated	moderate pro-nuclear
Scenario 2c	strong climate policy	low technical change	not concentrated	anti-nuclear
Scenario 3a	strong climate policy	high technical change	concentrated	strong pro-nuclear
Scenario 3b	strong climate policy	high technical change	concentrated	moderate pro-nuclear
Scenario 3c	strong climate policy	high technical change	concentrated	anti-nuclear
Scenario 4a	strong climate policy	high technical change	not concentrated	strong pro-nuclear
Scenario 4b	strong climate policy	high technical change	not concentrated	moderate pro-nuclear
Scenario 4c	strong climate policy	high technical change	not concentrated	anti-nuclear
Scenario 5a	low climate policy	low technical change	concentrated	strong pro-nuclear
Scenario 5b	low climate policy	low technical change	concentrated	moderate pro-nuclear
Scenario 5c	low climate policy	low technical change	concentrated	anti-nuclear
Scenario 6a	low climate policy	low technical change	not concentrated	strong pro-nuclear
Scenario 6b	low climate policy	low technical change	not concentrated	moderate pro-nuclear
Scenario 6c	low climate policy	low technical change	not concentrated	anti-nuclear
Scenario 7a	low climate policy	high technical change	concentrated	strong pro-nuclear
Scenario 7b	low climate policy	high technical change	concentrated	moderate pro-nuclear
Scenario 7c	low climate policy	high technical change	concentrated	anti-nuclear
Scenario 8a	low climate policy	high technical change	not concentrated	strong pro-nuclear
Scenario 8b	low climate policy	high technical change	not concentrated	moderate pro-nuclear
Scenario 8c	low climate policy	high technical change	not concentrated	anti-nuclear

Table V: 24 possible scenarios

It may not be relevant to describe all 24 scenarios without any kind of sorting: among the identified drivers for investments, we wanted to identify the ones that were the most relevant to scenario building, which was possible thanks to the processing of the structural analysis results with the MICMAC tool.

3.2 Sorting key drivers as a result of structural analysis

Using the Matrix of Direct Influences, the MICMAC tool generated the Graph of Direct Influences and Dependences, as shown in Figure 2. On this chart, the more a variable is far on the x-axis, the more it is dependent on other variables; the more a variable is far up the y-axis, the more it has influence on other variables. Therefore the variables contained in the upper left corner of the chart have influence on other ones but do not depend on them and are thus exogenous: they are called “input variables”. They tend to condition the system’s dynamics. The ones in the upper right corner of the chart, which have influence and depend on other variables, are called “intermediate variables”. They can sometimes be considered as the most important variables of the set since any action on these variables cascade throughout the rest of the system. The ones in the bottom right corner depend on other variables but have no influence on them: they are called: “output variables”. Their behaviors explain the impact from input and intermediate variables. The ones in the bottom left corner of the chart have no influence on other variables and do not depend on them: they are called “excluded variables” and are the less important ones. They often describe inertial trends that change little over time. Lastly, the “clustered variables” are the ones that are not sufficiently influential or dependent to be included among the previous classifications.

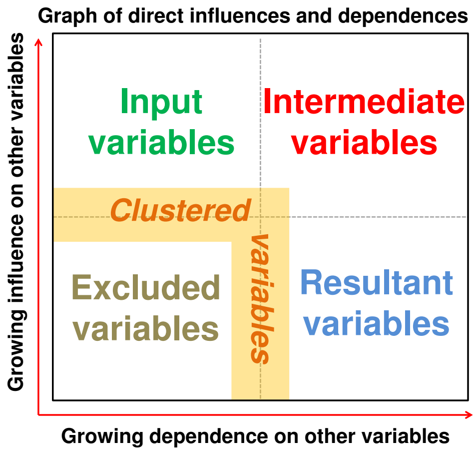

Figure 2: Chart of direct influences and dependences (empty)

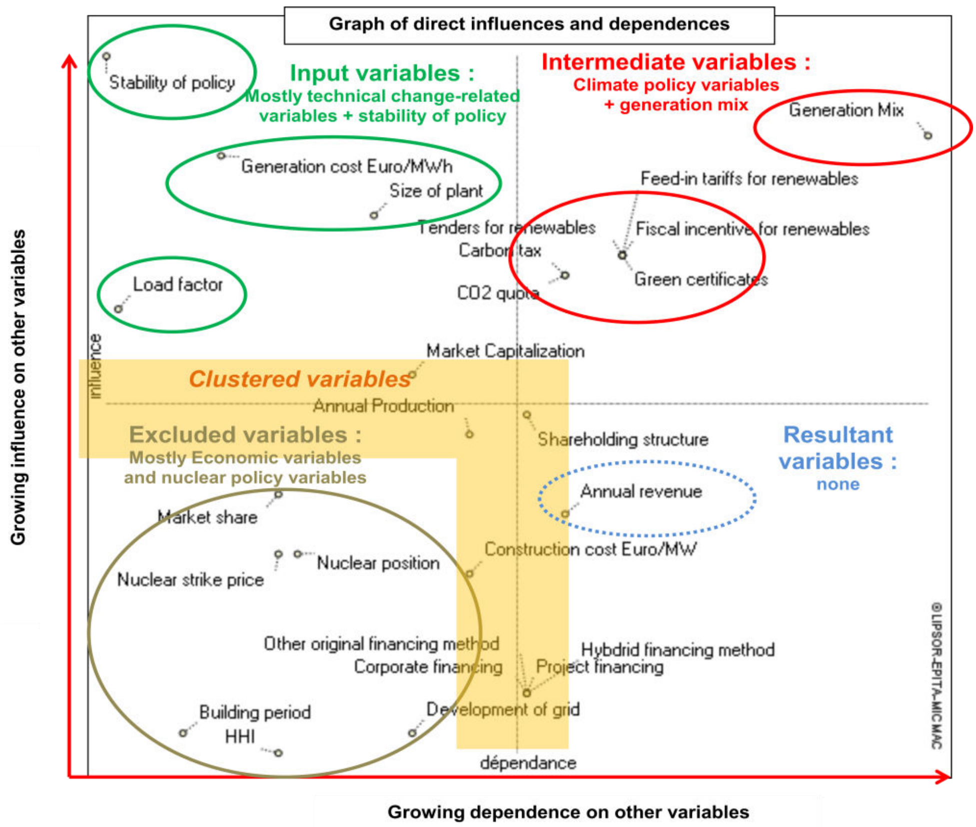

Figure 3: Chart of direct influences and dependences (external and internal variables)

Figure 2 shows that input variables are: policy stability and technical variables (generation costs, size of plant, load factor). Intermediate variables are all the climate policy variables and the generation mix. This is predictable since it means policy instruments are designed according to the technical characteristics of the technology. Nonetheless, technology changes cannot be seen as a direct result of policy (results of encouraging incentives are not direct enough). Generation mix is also a result of the technical characteristics of the technology and policies, as well as influencing the energy policy choices in return.

There are no resultant variables, except for the annual revenue that may considered as one: it is not surprising for this driver, since the annual revenue results from 1) the technology's characteristics such as generation costs, load factor and installed capacity (size of plant), 2) the company's generation mix, and 3) the policies adding or lessening the revenue. It also results from electricity prices, which was not listed among our drivers.

Excluded variables are most of the market driver-related variables: financing methods and the HHI, but also the 'construction timescale' technical variable and nuclear policy-related variables, which is coherent with our previous assumption according to which nuclear policy is invariant over time.

One striking result of this analysis is that all variables of market driver (the HHI, financing methods and grid development) have no influence whatsoever on the system and are excluded variables. This does not mean that they are not important individually for the investor when it comes to making a decision, but that they do not interact with other variables in the system composed by the identified drivers. This means that given the little direct interaction the market structure has with the other decision drivers, it will not change significantly over time. The financing methods – which are part of a more general issue of industrial financing (not only energy, not only electricity) – are more related to trends in the field of finance and banking.

Another striking result is that the company drivers are mostly clustered variables: it means that they have unclear influences that our structural analysis was unable to reveal, which is one of the limits of the tool. One counter-intuitive result is to have €/MW investment costs as a clustered variable, and not an input variable like generation cost. Clustered variables' role is not easily interpreted; however this could mean that it is not the cost per MW that really makes the investment capital-intensive, but the size of the plant, and also that the load factor indicates how fast the investment will be profitable

Lastly, the quasi-absence of resultant variables shows that there is no variable that can be influenced without cascading effects on other variables. In our investment choice problem, this means that there is no parameter easy to target to obtain a clear effect: a change in a policy or a technical driver will not have a clear and direct result on another driver, except for the revenue. This is consistent with the difficulty of defining efficient policies for instance, or to foresee the effects of technical progress.

3.3 4 Relevant types of scenarios

Relevant drivers to be applied when building scenarios are thus the climate policy and technical change, which leads to 4 main types of scenarios:

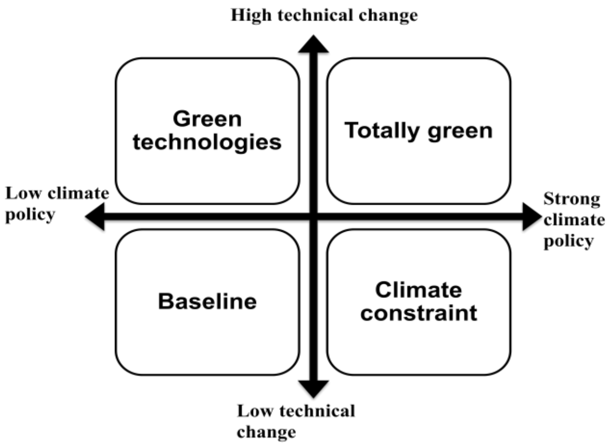

Figure 4: Main types of scenarios

In the baseline scenario, neither climate policy nor renewables know any significant upheaval. Carbon emission reduction still addressed by EU ETS market with low prices up to 4US$/ton$CO_2$, which is no strong incentive for carbon, except for UK who created a carbon tax that will increase as planned by the UK government. Current incentives for renewable will be pursued, some of them already being abandoned (as the solar FiT in Spain). It is the least favorable scenario to low-carbon technologies, but favorable to coal and gas. It consists in pursuing the same trends in all five countries: nuclear and fossil fuels with minor share of renewables in the UK and France, renewable and fossil fuels with minor share of renewables in Germany, Italy and Spain, meaning important carbon emissions. Fossil resources make it possible to continue using fossil-fueled electricity over the timescales considered (three decades). Nuclear development prospects will be only in France and UK (through building of EPRs), motivated by necessity of decommissioning of old plants, but the share of nuclear in their generation mix would not be likely to grow. The possibility of Fast Reactor penetration will exist in France according to French planning (Astrid project). In the end, nuclear development is supported only by pro-nuclear policies in UK and France.

The “green technologies” scenario states that renewables have achieved economic competitiveness through technical change, and there is a low climate policy. It introduces in the baseline scenario highly competitive renewables (the one predicted by the most optimistic assumptions). Since the results of the structural analysis suggest technology characteristics are the inputs for policy design, the incentives for renewables are made unnecessary by the economic competitiveness.

Like the baseline scenario, it is favorable to coal and gas investments but includes a “green” component. It is still favorable to renewables due to the technical change factor; gas investment will be promoted, since it is a low-capital, flexible technology technically suited to be a back-up capacity to renewable and economically suited to low load factors. More generally, among low-carbon technologies, this scenario tends to reduce nuclear investment in favor of gas and coal. For nuclear development, the same conclusion can be drawn, except that nuclear investments are less attractive given new competitive technologies on the market: nuclear is expected to lose market shares even in pro-nuclear countries.

The “totally green” scenarios, in which a strong climate policy is combined with high technical progress for renewables, are the most favorable to renewables and carbon emission reductions. Carbon prices will rise up to thanks to carbon tax or reform of carbon market. Renewable cost will decrease and at first be supported by strong incentives, which should attract investments. Renewables becoming competitive makes support policy useless, so the incentives should disappear at the latest after 20 years.

It is favorable to investment in both renewables and nuclear in France and the UK, and favorable to investment in renewables in Germany, Spain and Italy. In all countries, fossil-fuel-based technologies will lose market shares according to these scenarios. This means that back-up generation due to renewable intermittency will be ensured by non-intermittent hydraulic power and nuclear power. It is necessary to point out that such a situation means a lower load factor for nuclear power and thus an important loss of competitiveness on generation costs ((OECD and Nuclear Energy Agency, 2012). As a consequence, such massive low-carbon investment situations would be possible only if climate policies and renewable competitiveness were strong enough to maintain nuclear investment attractive compared with fossil fuels and especially gas, or if technical change could bring solutions to intermittency such as mastering long-term storage or interconnections between numerous sources. In terms of policy, the dynamics of the ‘totally green’ scenario would become similar to the ‘green technologies’ scenario in the last decade of the considered period, except for the carbon policy that would stay stronger, and renewable penetration would be lower in the ‘green technologies’ than in the ‘totally green’ scenario since not helped by incentives. As for nuclear development, interest in nuclear would be stronger than in the baseline scenario for France and UK. It would thus make development of Fast Reactor more likely in France and encourage pending investments in the UK through the renewing of 20 GW of nuclear and potential replacing of decommissioned coal fired power plants by nuclear (up to 8,3 GW).

The "climate constraint" scenario in which a strong climate policy faces low technical change in the renewables is favorable to low carbon time-tested technologies like nuclear and hydropower. However, in the five countries studied here, hydraulic capacities are already well developed and submitted to strong environmental constraints and local opposition, which considerably limits investment in new build. Considering the nuclear policies in the different countries in question, it is thus favorable to nuclear in France and the UK. In Germany, Italy, and Spain, this scenario should be favorable to renewables through climate policy incentives and despite their limited competitiveness. This scenario thus means the use of expensive renewable energies or the use of fossil fuels combined with high carbon prices for Germany, Italy and Spain. In any case, domestic electricity generation will be achieved at high costs. Nevertheless, the artificial maintenance of technologies that have not achieved economic profitability in the long term is questionable. As the results of the structural analysis suggest, technology characteristics are the inputs for policy design. This means that within a period of 20 years (which corresponds the longest lifetime of the incentives identified), the support for renewables should decrease. A strong climate policy means that support could go to newer technologies like CCS or geothermal energy. Still, since such technologies are further from maturity than wind and solar, their penetration would not be as good as that in the 'totally green' scenarios. An alternative solution could be found in electricity imports, depending on the development of the grid, being costly itself. This scenario is the one where there is the strongest interest in nuclear energy and thus in Fast Reactors. In France, nuclear capacity would definitely be maintained and investment in FR confirmed. Nuclear investments in the UK could cover not only the renewing of 20 GW of nuclear and the replacing of 8.3 GW of coal fired power plants, but also investments to respond to increasing demand and thus gain significant market shares. Investment in FR could thus be considered. As for Germany, Italy and Spain, the anti-nuclear stance could be questioned.

3.4 3 Scenarios for Gen IV integration

3.4.1 Identification of scenarios favorable to fast reactors

Among all types of scenarios, the "climate constraint" type of scenarios is thus the most favorable to nuclear investment and thus to FR integration. Let us clarify our point of view taking into account the neglected variables, market driver and nuclear policy: given that in the "climate constraint" context, nuclear seems the most viable solution, both moderate pro-nuclear and strong pro-nuclear stances would constitute favorable scenarios to nuclear development including FRs. In the market-related drivers, the most crucial ones are the financing methods that can, if well chosen, reduce the financial risk for investors. Market concentration factors will not be influential in this case since nuclear policy is supposed to ensure market coordination. Grid development is not an issue for centralized production means like nuclear plants.

"Totally green" scenarios are also favorable to nuclear investment, with the reserve expressed in subsection 2.3about their technical compatibility with intermittent technologies. It would need a strong pro-nuclear policy to allow for nuclear development until the stage of the next generation of reactors.

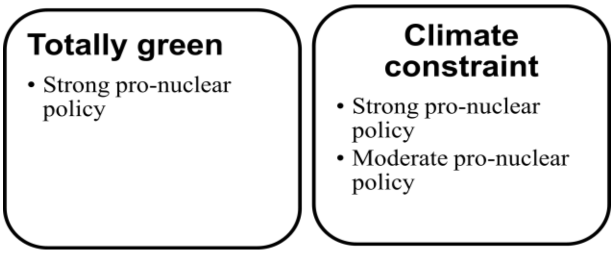

Figure 5: Three scenarios favorable to FR investments

We have thus identified the three scenarios that are the most likely to provide a favorable environment for investment in FRs. Let us not forget that these scenarios correspond to "necessary conditions" for FR development within our framework of assumption but not "sufficient conditions".

The next stage of the analysis consists in confronting the robustness of these results by observing what happens when we take the clustered variables out of the system.

3.4.2 Further analysis without the internal decision variables of investors

In this section, we exclude the company drivers, since these variables are clustered variables for most of them. The matrix of Direct Influences and Dependences is the same as in Table I, with the 20 first lines and 20 first columns[24].

Figure 5 shows the results of the MICMAC simulation performed without these variables (20 variables instead of 26).

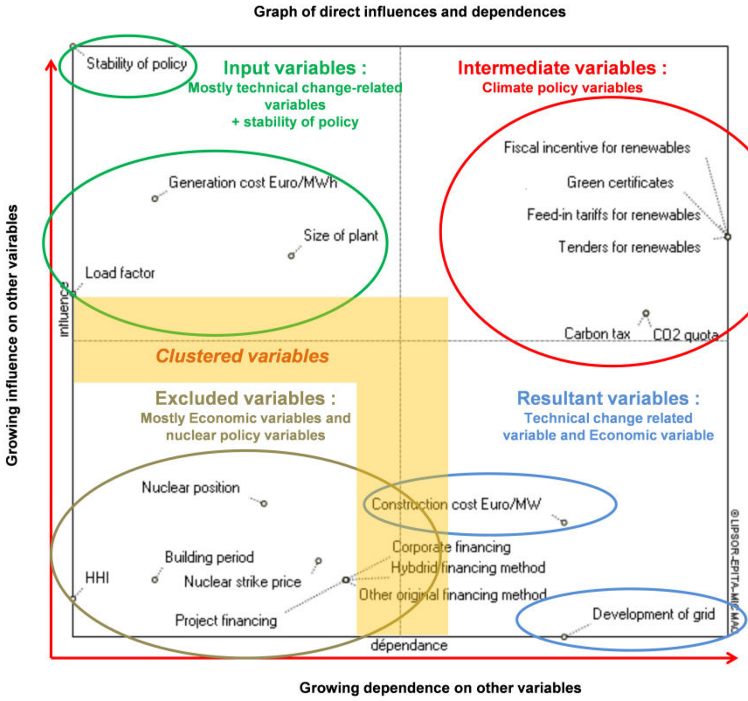

Figure 6: Chart of direct influences and dependences (external variables only)

The main tendencies of Figure 3 are clearly maintained, giving the same results regarding the relevant drivers for scenario building and confirming the robustness of the approach. However, two clustered or excluded variables appear here as resultant variables: construction costs and grid development. This means that the grid development will only be the result of policies and technology

[24] The filling rate of the matrix is 22.8%, which is close to the optimal filling recommended by Godet (2001).

changes. Let us not that in this chart €/MW investment costs as a resultant variable, and still not an input variable like generation cost. It confirms that it is not the cost per MW that really makes the investment capital-intensive, but the size of the plant, and that the load factor indicates how fast the investment will be profitable.

4 Conclusion

This chapter identifies the key drivers behind the choices of investors and construction scenarios for the European generation mix based on the development of these drivers in the future: 1) policy (divided into climate policy and nuclear policy), 2) technical change and 3) market drivers. The results of structural analysis and scenario discussion show that pro-nuclear policies are not enough to promote nuclear development in Europe: business-as-usual scenarios are not favourable to FRs; climate policy appears to be the *sine qua non* condition for further nuclear development. Surprisingly, the market driver is negligible compared with the two others. In the end, both strong and moderate pro-nuclear policies are compatible with FR investment in the "climate constraint" scenarios, where nuclear is the only economically viable alternative. The "totally green" scenarios combined to a strong pro-nuclear policy assumption are also favourable to FRs in a context of flourishing renewables. Three scenarios favourable to FR investment have thus been identified regardless of the market driver; that is to say, they gather the necessary conditions for FR investments.

Climate policy changes are thus determining for nuclear investment within our European scope. On a broader scale, the climate policy of Europe is decisive for the whole international climate policy: the achievement of its objectives would be a catalyst for an international climate policy, whereas its failure would discourage further attempts to build an international climate policy. Nevertheless, this does not mean that international FR development is bound to Europe as strongly. Other drivers such as a strong electricity demand due to quick industrialization could create an environment favourable to FRs for instance in Asia, even in case of unfavourable scenarios in Europe.

There are though a few limits to be mentioned: these scenarios only combine the necessary conditions for the emergence of FRs. There is also an indirect driver “public acceptance of the technology” that is, for now, included in the nuclear policy driver. However, public rejection could appear for renewables as well because of land use and landscape transformation. Among technologies omitted in this study, carbon capture and storage could change the attractiveness of fossil fuel in the “climate constraint” and “totally green” scenarios, while the development of FRs in the form of small modular reactors could change the analysis since the market concentration factor and, above all, grid development would mostly likely become more important.

5 References

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Chapter 3: Investment Choice Modeling based on Value Creation approach

The previous chapter identified in a detailed manner the drivers intervening in electricity investments and how they interact with each other, and how this can shape the future. This chapter aims at going deeper in taking an investor's perspective regarding those choices by defining a tool to replicate investors' choices. Based on the results of structural analysis conducted in Chapter 2, a value creation approach allows identifying the stakeholders in interaction with the electricity company regarding investment choice in power generation capacity. The value pursued by every stakeholder is then defined; the analysis then focuses on maximizing the value for the power company, leading the development of a tool based on Design Structure Matrix and Quality Function Development Matrix methods. This tool uses the identified drivers to assess the compatibility of an investor (i.e. a power generating company) with a technology, including technical, but also policy and market drivers associated with the technology. Technology preferences are thus modeled for a set of companies in the scope under study and in the three scenarios retained by structural analysis. These preferences are then used to quantify companies' preferences into investment choices and built the corresponding generation mix for the considered countries.

1 Value creation approach

1.1 Literature review

When a power company invests in new capacities to maintain or increase its economic activity, they expect to achieve value creation through this investment. Historically, the only value considered was economic value created by a product and the measured indicators costs and benefits; with the increase of supply in the seventies, competition became fiercer between companies and the concept of value creation evolved to take into account product quality, on-time delivery (Lebas, 1995), and later, knowledge, know-how, innovation (Le Masson et al., 2006). The scope of value creation also evolved from being narrowed to the product only to including the whole organization (Le Masson et al., 2006). Increasing importance of environmental issues in the 1990s made companies worry about image and acceptability of their activities, and thus pursue social, environmental and ethical value creation (Déjean and Gond, 2003). In the end, the concept of value creation shifted from the creation of economic value (cost-benefit) of one product to the creation of multiple values (cost-benefit but also quality, ethics…) by one organization (Schindler, 2009).

Considering multiple value creations by an organization makes it necessary to take into account all stakeholders affected by these value creations: the company entertains bi-lateral relationships with these stakeholders (Donaldson and Preston, 1995). They ‘can affect or be affected by the achievement of the organization’s objectives’ (Freeman, 1984) and can thus represent both help or threat for the company (Petetin, 2012). The classic approach consists in decomposing internal and external stakeholders (Carroll and Näsi, 1997). Several typologies exist, offering various decomposition such as primary stakeholders (linked to the organization through a contract: employees, suppliers, customers…) and secondary stakeholders (competitors, local authorities) (Carroll and Buchholtz, 2000); or the systemic view of stakeholders by Schindler, resulting from the analysis of different management theories (Schindler, 2009).

The following paragraphs apply this approach to our case study, identifying the stakeholders and value creation they pursue.

1.2 Identification of stakeholders

In Chapter 2, four main groups of drivers are identified thanks to structural analysis: state policy drivers, market drivers, technical drivers and company drivers. We can deduce from stakeholders related to each group of drivers: state actors such as governments, ministries, or the European Commission control policy drivers. Market actors include regulators to control respect of competition rules in order to promote liberalization, grid managers to connect markets, financing organisms to provide financing options to investors. Let us not forget that competitors, that is to say other electricity companies, are also market actors. Technology developers are the stakeholders related to technical change and technology promotion. The last major stakeholders are the customers, since they trigger demand. Since demand was not identified as a driver in the European context, due to low demand growth and high level of installed capacity, we do not consider the ‘customer’ stakeholder as interacting with the others in this case study. Demand will be considered as exogenous and little growing, mostly trigged by capacity renewal issues. The table below sums up shareholders identified thanks to the drivers.

Variable	Related Driver	Related Stakeholder
Carbon tax (€/tCO_2)	Policy Driver	State actors : Government, Ministries, European Union
CO_2 quota		
Feed-in tariffs for renewables (€/MWh)		
Green certificates for renewables		
Tenders for renewables		
Fiscal incentive for renewables		
Nuclear position		
Nuclear strike price (€/MWh)		
Stability of policy		
HHI concentration index	Market Driver	Market actors: o Competitors o Grid managers o Regulators o Financing organisms
Development of grid and interconnections		
Corporate financing		
Project financing		
Hybdrid financing method (corporate and project financing)		
Other original financing method		
Construction costs (€/MW)	Technical Change Driver	Technology developers
Generation costs (€/MWh)		
Building period (year)		
Size of plant (MW)		
Load factor (%)		
Shareholding structure	Company driver	Power company
Market Capitalization		
Annual Production		
Generation Mix		
Market share		
Annual revenue		

Table IX: Shareholders associated with main drivers for investment choices

The identified stakeholders are well adapted to the classic decomposition (Carroll and Näsi, 1997) between an internal stakeholder: the power company and external stakeholders: state actors, market actors, technology developers. The purpose of the study is to understand how the internal stakeholder maximizes its value creation taking into account the fact that external stakeholders are also trying to maximize their value creation.

1.3 Value creation for each stakeholder

The different stakeholders aim at creating different types of values, although they also happen to have common value creation goals. In this paragraph we seek to identify these different types of values in the cases of the stakeholders identified above. The literature review and interviews conducted for structural analysis (see Chapter 2) allow listing these values.

State actors aim first at security of supply and energy independency, which we will list as a 'security value'. Economic value is also essential on several levels to them. In order to support national economy, they are keen to favor affordable and secure supply of households and industries; technological advancement as a competitive advantage is also an important preoccupation. Last, since state actors are sometimes involved in power companies as stakeholders, they have a direct interest in the company achieving high revenues and benefits. They also seek fair supply of all customers on the territory, which is a social value, and to protect the environment especially regarding climate issues and technological hazard (environmental value).

Market actors chase very different values: grid managers aim at good grid quality i.e. ensuring secure supply with no cuts or black-outs; regulators want to promote competition; while financing organisms are going after economic value through their shares or loans to the investing power companies. Competitors have the same goals as the power company stakeholder.

Technology developers aim at technological progress and promotion of their technology; they can be partly or totally included in the power company depending on how much the latter participates in capacity construction.

Power companies aim at security in priority, which means having guaranteed revenue out of their investment; they also seek to increase this revenue (economic value) and gain more market shares (competition value).

Theses value creations are summarized in Table X and associated with the corresponding stakeholders in Table XI.

security value
guarantee of long-term revenu
secure supply
energy independency
economic value
affordable supply
technological advancement as a competitive advantage
revenue
social value
supply for all citizens
environmental value
environment and climate protection
competition value
efficient competition
gain market share
technological value
promotion and progress of technology

Table X: Value creation associated with electricity investment

State actors : Government, Ministries, European Union	**economic value:** affordable and secure supply for citizens and industries technological advancement of the coutry revenue (as a stakeholder)
	social value: supply of all citizens
	security value: energy independency
	environmental value: climate and environment protection
Market actors:	
o Competitors	same as 'Company' stakeholder
o Grid managers	**security value:** secure supply
o Regulators	**competition value:** efficient competition
o Financing organisms	**economic value:** revenue (as a stakeholder)
Technology developers	**technological value:** promotion and progress of technology
Power company	**security value:** guaranteed revenue
	competition value: gain market shares
	economic value: revenue

Table XI: expected value creation for each stakeholder

Now that we have defined which values stakeholders aim at creating, we analyze how the value creation can be measured. Measuring the performance in creating the expected value will then allow identifying the means stakeholders use to obtain value when it comes to electricity investment, and especially the power company.

1.4 Measuring performance of value creation

For state actors, the 'security value' performance can be measured through quality of supply and energy independency indicators. Economic value will be evaluated through electricity prices, export of national technologies, and company revenues. Social value of customer supply will also be measured by a quality of supply indicator. Environment value performance can be assessed through GHG emissions evolution.

In the case of market actors, grid quality performances can be measured through a grid quality indicator; success of competition through prices, with the limitations mentioned in Chapter 2; economic value sought by financing organisms can be measured through company revenues and interest rates.

Technological progress and promotion of a technology will be evaluated through learning effects in technology costs and evolution of its share in the electricity mix.

As for power companies, achieving secure revenue and economic value can be assessed through the companies' characteristics such as the amount of revenue itself, the amount of generation; performance of the 'competition value' can be assessed through the evolution of the company's market share, both in generation and installed capacity can be measured through the amount of power generation, evolution of installed capacity. We can see that the indicators for the company's performance regarding value creation are the 'company drivers' from Chapter 2[25]: for the internal stakeholder, electricity investment choices are driven by performance indicators of its value creation, which is consistent.

The performance indicators for each value creation and stakeholder are summarized in Table XII.

[25] The 'market capitalization' driver though consistent as an indicator financial size of the company and financial value in a competition context, is not kept in this approach because it its value is too volatile to have significance in long-term projections over several decade.

Stakeholders / Value	Power company	State	Market : competitors	Market: grid manager	Market: regulator	Market: financing organism	Technology developer
security value							
guarantee of long-term revenu	generation, sale, generation mix		generation, sale, generation mix				
secure supply		supply quality indicator		grid quality indicator			
energy independency		energy independency indicator					
economic value							
affordable supply		electricity prices					
technological advancement as a competitive advantage		technology export					
revenue	revenue and costs mix evolution	revenue and profit (as a shareholder	revenue and costs mix evolution			revenue and profits of the company, interest rates	
social value							
supply for all citizens		supply quality indicator					
environmental value							
environment and climate protection		GHG emissions evolution					
competition value							
efficient competition					electricity prices		
gain market share	market share, installed capacity, power generation		market share, installed capacity, power generation				
technological value							
promotion and progress of technology	progress of technology in the mix						learning effects and progress of technology in the mix

Performance indicators

Table XII: Measuring value creation performance

1.5 Stakeholder action to achieve value creation

In this paragraph, we use the performance indicators for value creation in order to determine the means that stakeholders implement to achieve value creation. We can see that these means implemented by stakeholders basically correspond to the related drivers: policy drivers, market drivers and technical change drivers.

In order to achieve high value creation materialized through electricity prices, technology export, power company high revenue, supply quality indicator and decreasing GHG emissions, state actors implement policies to support some energies and disadvantage others: energy policy that mainly consist today in climate policy including carbon reduction and renewables promotion, and nuclear policy, that is to say the policy drivers.

Likewise, market actors aim at achieving their creation value through the market drivers: grid development to achieve good grid quality for grid manager, market de-concentration to achieve competitive prices for the regulator, and adapted financing options to ensure better returns for financing organisms. Technology developers aim at promoting their technology thanks to improvements in costs and performances.

However, it is necessary to mention that even if these drivers are means for the stakeholders to achieve value creation, it does not mean that they have entire control on it. Grid development, market concentration and technical change drivers are partly exogenous, partly affected by other drivers, as we saw in Chapter 2.

Last, the power company's way of achieving value creation is the choice of technology they make when investing in power generating capacities, which is the heart of this study. The choice of technology has to ensure high revenues and levels of generation, high installed capacity and market share, promotion of the technologies the company is mostly involved with and potentially achieve state actors' value creation depending on if the state owns shares of the company. This choice also has to take into account all the means that external stakeholders use to achieve their own value creation, that is to say external drivers. In the end, the power generation company maximizes their creation value when choosing the technology that allows the best compatibility between internal drivers and external drivers. Flows of influences and dependences between drivers have already been identified and quantified in Chapter 2. In the next paragraph, we use these previous results and focus on the particular issue of compatibility between external and internal drivers in order to propose a tool replicating the power company's choice.

Table XIII recapitulates for each stakeholder the sought value, the performance indicator for value creation, and the means to achieve value creation.

Stakeholder	Wanted value creation	Value creation performance	Mean to create wanted value
Power company	**security value:** guaranteed revenue	generation, sale, generation mix	Investment choice in a technology
	competition value: gain market shares	market share, installed capacity, power generation	
	economic value: revenue	revenue and costs mix evolution	
	values for state actor depending on state implication in company	state actor's market share	
	technological value: promotion and progress of technology	evolution of technology in generation mix	
State actors : Government, Ministries, European Union	**economic value:** affordable and secure supply for citizens and industries technological advancement of the coutry revenue (as a shareholder)	electricity prices technology export revenue and profit (as a shareholder	Energy policy and incentives: climate policy - CO_2 incentive, - renewable incentive nuclear policy: - nuclear stance, - nuclear incentive
	social value: supply of all citizens	supply quality indicator	
	security value: energy independency	energy independency indicator	
	environmental value: climate and environment protection	GHG emissions evolution	
Market actors:			
o Competitors	same as company stakeholder	same as company stakeholder	same as company stakeholder
o Grid managers	**security value:** secure supply	grid quality indicator	grid development
o Regulators	**competition value:** efficient competition	electricity prices	concentration
o Financing organisms	**economic value:** revenue	revenue and profits of the company, interest rates	financing options
Technology developer (sometimes same as power company)	**technological value:** promotion and progress of technology	learning effects and progress of technology in the mix	improvement of cost and performance

Table XIII: Means to achieve value creation for each stakeholders in electricity investment

2 Focus on value creation for the company: building of investment preference model

In this paragraph, we want to build a tool in order to determine what technology choice offers the best compatibility between company drivers and external drivers when an investment has to be made. In Chapter 2, influences of drivers upon another were modeled in a matrix called the matrix of direct influences and dependences within the MICMAC tool. Now, we want to assess compatibility between internal and external drivers in the case of each considered technology, in order to establish the power company's preference. In the continuity of the use of the MICMAC tool, we thus go through Design Structure Matrix literature on matrix tools to find a method suited to this case. We then build a model aiming at replicating power companies' choices in order to apply it to the scenarios defined in Chapter 2.

2.1 Literature review

Design structure matrix are originally a tool for system engineering of products, processes and organizations (Browning, 2001). Since they allow management of complex system in pretty much any discipline, they have more and more applications, to issues such as health care management, financial systems, public policy, natural sciences, and social systems (Eppinger and Browning, 2012). The use of Design Structure Matrix in the prospective tool MICMAC is one example among them. The review of main DSM applications by (Browning, 2001) distinguish two types of DSMs: static DSMs represent system elements existing simultaneously, while time-based DSMs represent time flow through the ordering of lines and columns. The MICMAC approach used in Chapter 2 clearly belongs to the static DSM type, as well as the one developed in this chapter, since the purpose is to analyze simultaneous influences of drivers at the time of investment decision. Among DSM applications, the case of company choice for electricity investment can be considered as a New Product Development Process as in (Karniel and Reich, 2011), the new product being the new electricity capacity to be invested in. The different power generation technologies are then the different options for product design. Evaluating the compatibility between company drivers and external drivers can be done through the use of a compatibility matrix (Hellenbrand and Lindemann, 2008); since the confronted domains are not the same (company drivers on the one hand, external drivers on the other), the matrix is rectangular and not square contrary to the MICMAC matrix and to most DSM applications: it is a Domain Mapping Matrix DMM (Eppinger and Browning, 2012).

In the next paragraph explains the method for the filling of the matrix to quantify compatibility between drivers.

2.2 Compatibility matrix

Table XIV shows the DMM to be filled to assess compatibility between the company and a technology affected by all external drivers.

		Power company					
		Part of state actors in the shareholding structure	Installed Capacity	Annual Production	Part of technology in generation Mix	Market share	Annual revenue
State actors	Carbon price						
	Incentive for renewables						
	Number of incentives for renewables						
	Incentive for nuclear						
	Stability of policy						
Market actors: o Regulators and Competitors o Grid managers	HHI						
	Development of grid						
Technology developers	Construction cost Euro/MW						
	Generation cost Euro/MWh						
	Building period						
	Size of plant						
	Load factor						
Market actors: o Financing organisms	Corporate financing						
	Project financing						
	Hybdrid financing method						
	Original financing method (customer)						

Table XIV: Compatibility matrix for internal and external drivers (empty)

The first step for the filling of the matrix consists in locating the boxes where compatibility has to be assessed due to the existence of a relationship between the drivers. This information is easily provided by the matrix of Direct Influences and Dependences filled in Chapter 2, reminded here as Table XV. The observation of relationships between drivers in both ways (influences and dependences) in this table allows indicating internal and external drivers related to one another in Table XVI.

Stakeholder	Variable	1 : Carbon tax	2 : CO2 quota	3 : Feed-in tariffs for renewables	4 : Green certificates	5 : Tenders for renewables	6 : Fiscal incentive for renewables	7 : Nuclear position	8 : Nuclear strike price	9 : Stability of policy	10 : HHI	11 : Development of grid	12 : Construction cost Euro/MW	13 : Generation cost Euro/MWh	14 : Building period	15 : Size of plant	16 : Load factor	17 : Corporate financing	18 : Project financing	19 : Hybdrid financing method	20 : Other original financing method	21 : Shareholding structure	22 : Market Capitalization	23 : Annual Production	24 : Generation Mix	25 : Market share	26 : Annual revenue
		State								Market: Grid and regulator		Technology developer					Market: Financing organisms				Power company						
State	1 : Carbon tax	0	3	3	3	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	3	0	3
State	2 : CO2 quota	3	0	3	3	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	3	0	3
State	3 : Feed-in tariffs for renewables	3	3	0	3	3	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
State	4 : Green certificates	3	3	3	0	3	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
State	5 : Tenders for renewables	3	3	3	3	0	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
State	6 : Fiscal incentive for renewables	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
State	7 : Nuclear position	4	4	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	0
State	8 : Nuclear strike price	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
Market: Grid and regulator	9 : Stability of policy	3	3	3	3	3	3	3	3	0	0	3	0	0	0	0	0	1	1	1	1	3	0	0	3	0	0
Market: Grid and regulator	10 : HHI	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Technology developer	11 : Development of grid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
Technology developer	12 : Construction cost Euro/MW	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	3	0	2	0	0
Technology developer	13 : Generation cost Euro/MWh	3	3	3	3	3	3	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	3	3	3	0	3
Technology developer	14 : Building period	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Technology developer	15 : Size of plant	0	0	0	0	0	0	0	0	0	0	2	3	0	3	0	0	3	3	3	3	0	0	3	3	3	0
Market: Financing organisms	16 : Load factor	0	0	3	3	3	3	0	0	0	0	3	0	0	0	3	0	0	0	0	0	0	0	3	3	0	0
Market: Financing organisms	17 : Corporate financing	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Market: Financing organisms	18 : Project financing	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Market: Financing organisms	19 : Hybdrid financing method	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Power company	20 : Other original financing method	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Power company	21 : Shareholding structure	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	3	3	3	0	3	0	3	0	0
Power company	22 : Market Capitalization	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3	0	3	3	3	3	3	0	0	0	0	0
Power company	23 : Annual Production	0	0	0	0	0	0	0	0	0	3	3	0	3	0	2	1	0	0	0	0	0	0	0	0	3	3
Power company	24 : Generation Mix	3	3	3	3	3	3	2	0	0	0	3	1	0	1	1	0	1	1	1	1	0	0	3	0	0	0
Power company	25 : Market share	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3	3	3	3	0	0	0	0	0	0
Power company	26 : Annual revenue	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	0	3	0	0	3	0

Table XV : Matrix of Direct Influences and Dependences with corresponding stakeholders

		Power company					
		Part of state actors in the shareholding structure	Installed Capacity	Annual Production	Part of technology in generation Mix	Market share	Annual revenue
State actors	Carbon price	x	0	x	x	0	x
	Incentive for renewables	x	0	0	x	0	x
	Number of incentives for renewables	x	0	0	x	0	x
	Incentive for nuclear	x	0	0	x	0	x
	Stability of policy	x	0	0	x	0	0
Market actors: o Regulators and Competitors o Grid managers	HHI	0	x	0	0	x	0
	Development of grid	0	0	x	x	0	0
Technology developers	Construction cost Euro/MW	0	x	0	x	0	0
	Generation cost Euro/MWh	0	x	x	x	0	x
	Building period	0	0	0	x	0	0
	Size of plant	0	x	x	x	x	0
	Load factor	0	0	x	x	0	0
Market actors: o Financing organisms	Corporate financing	x	x	0	x	x	x
	Project financing	x	x	0	x	x	x
	Hybdrid financing method	x	x	0	x	x	x
	Original financing method (customer)	x	x	0	x	x	x

Table XVI: Compatibility matrix: identification of boxes to be filled

The matrix of direct influences and dependences also allows weighing the corresponding boxes with the importance of the reciprocal relationship between drivers: for this, we sum the indicators of relationship importance in both ways, which gives the weights presented in Table XVII.

		Power company					
		Part of state actors in the shareholding structure	Installed Capacity	Annual Production	Part of technology in generation Mix	Market share	Annual revenue
State actors	Carbon price	2	0	2	6	0	3
	Incentive for renewables	2	0	0	6	0	3
	Number of incentives for renewables	2	0	0	6	0	3
	Incentive for nuclear	2	0	0	3	0	3
	Stability of policy	3	0	0	3	0	0
Market actors: o Regulators and Competitors o Grid managers	HHI	0	3	0	0	3	0
	Development of grid	0	0	6	3	0	0
Technology developers	Construction cost Euro/MW	0	3	0	3	0	0
	Generation cost Euro/MWh	0	3	6	3	0	3
	Building period	0	0	0	1	0	0
	Size of plant	0	3	5	4	3	0
	Load factor	0	0	4	3	0	0
Market actors: o Financing organisms	Corporate financing	3	4	0	2	3	2
	Project financing	3	4	0	2	3	2
	Hybdrid financing method	3	4	0	2	3	2
	Original financing method (customer)	3	4	0	2	3	2

Table XVII: Compatibility matrix: assessement of weights for filled boxes

Last, since the compatibility has to be assessed for different technologies, policies, and companies, the quantification of this compatibility has to be a function of both drivers involved. The compatibility function needs to reflect the effects of drivers' value variation. For instance, regarding the compatibility of the internal driver 'revenue' and the external driver 'carbon price': the higher the company's revenue is, the better it is for the company's value creation. On the other hand, the higher the carbon price gets, the less favorable it is for the company's revenue. The compatibility function is thus increasing of revenue and decreasing of carbon price. The simplest way of describing such a phenomenon is to model the compatibility function f of external driver x internal driver y as a linear combination of two functions f1 of x and f2 of y:

$f(x,y) = f_1(x) + f_2(y)$

with f_1 and f_2 two linear functions, increasing or decreasing according to the role of the driver towards the company's value creation.

with $x_{min} < x < x_{max}$

and $y_{min} < y < y_{max}$

x_{min} and x_{max}, y_{min} and y_{max} being the extrema found in literature or empirical data for the driver's value (for instance, installed capacity of a power company in our scope ranges from 15 to 100 MW, according to annual reports of companies). In order to normalize f between 0 and 1, f_1 and f_2 finally take the following form:

When f_1 is an increasing function of x: $(x - x_{min}) \big/ 2(x_{max} - x_{min})$

When f_1 is a decreasing function of x: $-(x - x_{max}) \big/ 2(x_{max} - x_{min})$

When f_2 is an increasing function of y: $(y - y_{min}) \big/ 2(y_{max} - y_{min})$

When f_2 is a decreasing function of y: $-(y - y_{max}) \big/ 2(y_{max} - y_{min})$

In the case of ‘yes or no’ drivers (for instance: presence of an incentive for nuclear or not), quantification is binary (0 or 1). In the few cases where f is a function of only one driver, f takes the following form:

When f is an increasing function of x: $(x - x_{min}) / (x_{max} - x_{min})$

When f is a decreasing function of x: $-(x - x_{max}) / (x_{max} - x_{min})$

Table XVIII gives the complete version of the compatibility matrix ready for use.

		Power company											
		Part of state actors in the shareholding structure		Installed Capacity		Annual Production		Part of technology in generation Mix		Market share		Annual revenue	
	max and min values	*0-85%*		*15-100 MW*		*60-600 TWh*		*0-80%*		*3-80%*		*10-120 G€*	
		weight	*compatibility index*	*weight*	*compatibility index*	*weight*	*compatibility index*	*weight*	*compatibility index*	*weight*	*compatibility index*	*weight*	*compatibility index*
Carbon price	*0,05-74 €/kWh*	2	f1 decreasing f2 increasing	0		2	f1 decreasing	6	f1 decreasing f2 decreasing	0		3	f1 decreasing f2 increasing
Incentive for renewables	*yes/no*	2	0/1	0		0		6	0/1	0		3	0/1
Number of incentives for renewables	*number [0,4]*	2	f1 increasing	0		0		6	f1 increasing	0		3	f1 increasing
Incentive for nuclear	*yes/no*	2	0/1	0		0		3	0/1	0		3	0/1
Stability of policy	*duration 5-20 years*	3	f1 increasing f2 decreasing	0		0		3	f1 increasing	0		0	
HHI	*value 800-7000*	0		3	f1 decreasing f2 decreasing	0		0		3	f1 decreasing f2 decreasing	0	
Development of grid	*yes/no*	0		0		6	f1 decreasing f2 increasing	3		0		0	
Construction cost Euro/MW	*500-6000 €/kW*	0		3	f1 decreasing f2 increasing	0		3	f1 decreasing f2 increasing	0		0	
Generation cost Euro/MWh	*80-200 €/MWh*	0		3	f1 decreasing f2 increasing	6	f1 decreasing f2 increasing	3	f1 decreasing f2 increasing	0		3	f1 decreasing f2 increasing
Building period	*1-10 years*	0		0		0		1	f1 decreasing f2 increasing	0		0	
Size of plant	*2-1600 MW*	0		3	f1 decreasing f2 increasing	5	f1 decreasing f2 increasing	4	f1 decreasing f2 increasing	3	f1 decreasing f2 increasing	0	
Load factor	*25-90%*	0		0		4	f1 increasing	3	f1 increasing f2 increasing	0		0	
Corporate financing	*yes/no*	3	f1 increasing f2 increasing	4	f1 increasing f2 increasing	0		2	f1 increasing f2 increasing	3	f1 increasing f2 increasing	2	f1 decreasing f2 decreasing
Project financing	*yes/no*	3	f1 increasing f2 decreasing	4	f1 increasing f2 increasing	0		2	f1 increasing f2 increasing	3	f1 increasing f2 increasing	2	f1 decreasing f2 decreasing
Hybdrid financing method	*yes/no*	3	f1 increasing f2 decreasing	4	f1 increasing f2 increasing	0		2	f1 increasing f2 increasing	3	f1 increasing f2 increasing	2	f1 decreasing f2 decreasing
Original financing method (customer)	*yes/no*	3	f1 increasing f2 decreasing	4	f1 increasing f2 increasing	0		2	f1 increasing f2 increasing	3	f1 increasing f2 increasing	2	f1 decreasing f2 decreasing

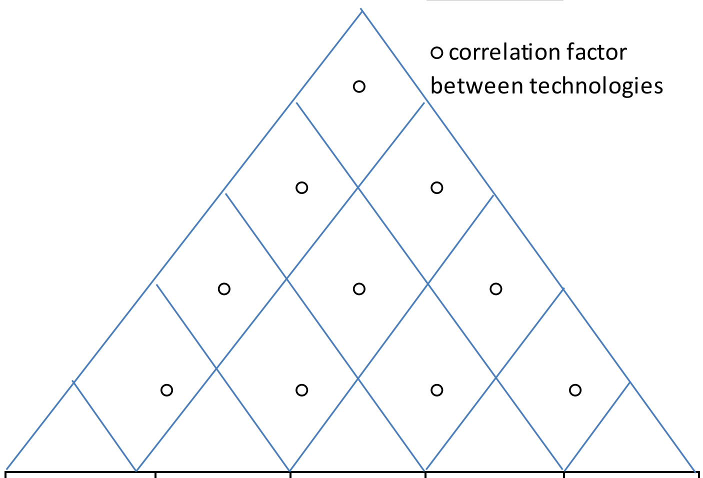
Table XVIII: Compatibility matrix with minimum and maximum values

When filled with the drivers' values relative to one technology and one company in lines and columns, the matrix gives a compatibility values in each non-zero box. The compatibility values can be aggregated in compatibility index normalized between 0 and 1 for each columns, that is to say for each company driver, and in a global index for the whole matrix, also normalized between 0 and 1. The compatibility index then allows to sort technologies from the most compatible (preferred one) to the least compatible.

2.3 Investment choice modeling

When confronted to an investment opportunity, the company's preferences are thus given by the aggregated compatibility index and technologies can be ranked for the preferred one to the least preferred one. When the preferred technology is a manageable one (i.e. gas, nuclear or coal), we consider that it constitutes the totality of the capacity built. However when the preferred technology is an intermittent renewable technology, a minimum of back-up capacity should also be installed since exclusive building of intermittent renewable is not feasible – except for small capacities - there is a limit for renewable penetration in the mix due to system effects (OECD-NEA, 2012). Although such constraint may not exist in the next decades thanks to technological progress of electricity storage systems, there is yet no guarantee to solve it and though consider it as a constraint for the whole studied period (2012-2040). A more sophisticated modelling has thus to be adopted in order to both reflect investor's preferences and take into account technological feasibility. Consistently with the fact that renewables are usually built as small capacities, the compatibility index for renewables is very sensitive to plant size. The default value being the standard size of a plant: 50 MW for a wind farm, 2 MW for a solar farm (OECD-NEA, 2010), building important capacities of these technologies quickly reduces the compatibility index of the technology. For this reason, when the preferred technology is an intermittent renewable technology and the second preferred technology a manageable one (gas, nuclear, coal), the installed capacity for each technology is assessed as follows: installed capacity of renewable is increased until the compatibility index falls to the same level as the second preferred technology, and remaining capacity to install is divided equally between the two technologies. When the two preferred technologies are intermittent renewables however, installed capacity of the first preferred technology is increased until the compatibility index falls to the same level as the second preferred technology, and remaining capacity to install is divided equally between renewables on the one hand, and the manageable capacity on the other hand. This last case has a limit in a sense that it undermines the preference of the investor for the second technology over the third technology in order to integrate manageable capacity investment.

When compatibility indexes are close and do not allow clear choice, a Quality Function Deployment matrix as in Table XIX can help clarify the choice by assessing how substitutable one technology is to another through the correlation factor. The correlation factor being the sum of the gaps between compatibility values for each company drivers, it shows how much alike two technologies are in terms of creation value for the company. Concretely, it usually underlines the complementarity of baseload and peak capacities and most of all manageable and unmanageable generation technologies. However, the lowest correlation factors between two technologies are also the sign of a gap between a technology with good performances regarding value creation for the company and a technology with mediocre performances in the matter. This is why the correlation factor of the Quality Function Deployment only helps to choose complementary technologies for the top-ranking technologies when compatibility indexes are close and do not allow clear choice.



	Weight	Nuclear	Coal	Gaz	Solar	Wind
Compatibility with Shareholding structure	23	column index				
Compatibility with Size : Installed Capacity	28	column index				
Compatibility with Size : Annual Production	23	column index				
Compatibility with Generation Mix	49	column index				
Compatibility with Market share	18	column index				
Compatibility with Annual revenue	23	column index				
	Sum of weights 164	aggregated index				

Table XIX: Quality Function Deployment Matrix for the different technologies at stake

This method thus allows modeling the choice made by an electricity company when faced with an investment opportunity.

In order to see the impact of companies' preferences on the generation mix of the studied countries, the method is applied to the major electricity companies in these countries, in the three favorable scenarios identified in Chapter 2. Investment is thus determined to the companies' level, and then aggregated to give installed capacity mix at a national level. Those installed mix are then converted to generation mix using load factors of technologies (see Annex 6.3 and 6.4).

3 Results: application to scenarios

This section presents the results of the compatibility matrix applied to the scenarios defined in Chapter 2, reminded in Figure 7 below.

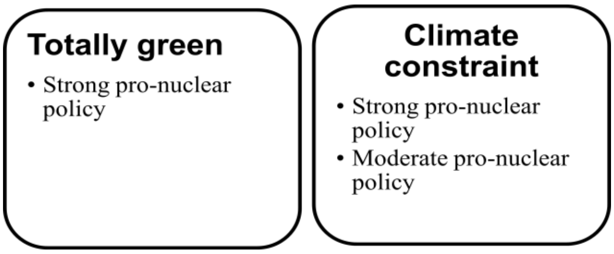


Figure 7: Three scenarios favorable to SFR investments

3.1 Scenario hypothesis

The scope is France, Germany, Italy, Spain and their main electricity producers presented in Table XX.

France	Germany	Italy	Spain	UK
EDF	EOn	Enel	Endesa	Centrica
	RWE	EOn	Iberdrola	Scottish and Southern Energy
	EnWB	EDF	Gas Natural Fenosa	EDF Energy
	Vattenfall	Eni	EDP	Scottish Power/Iberdrola
			EOn	EOn
				Npower/RWE

Table XX: Main power generators in our scope

Given the age of European power plants and market share of every company, retiring capacities have been assessed for every company (see Annex 6.2). Since demand is not expected to grow much in Europe and even sometimes to decrease in high energy efficiency scenarios (Grand and Veyrenc, 2011; IEA, 2012b), we only consider capacity renewing as power investments during the 2012-2040 period. The purpose being to get major trends rather than accurate estimations, this limit is not crippling for the consistency of this work.

All scenario rely on a strong climate policy, which consists in a carbon price rising up to 90 €/tCO_2 in 2040. Two periods are considered, 2012-2025, during which the price of carbon is at an intermediate level of 45 €/ tCO_2 and 2025-2040, during which the price of carbon is at its final level 90 €/tCO_2. Carbon cost per MWh is then calculated in the compatibility matrix according to every technology's level of emission per MWh (see Table XXI below).

Technology	coal	gas	solar PV	nuclear	wind	hydro
kg CO_2 eq/MWh	820	420	45	15	14	6

Table XXI: CO2 emissions per MWh according to technology, *source: European Commission, 2009*

Regarding costs, change is expected only in recent renewables, with a low technical change hypothesis in the Climate Constraint scenarios, and a high technical change hypothesis in the Totally Green scenario. The following tables contain the cost estimations used for low and high technical change scenarios. These generation costs were calculated using the cost data of WEO 2012 (IEA, 2012b) and according to the LCOE methodology with a 10% discount rate as in the OECD-NEA report (OECD-NEA, 2010).[26]

Technology costs (€/MWh)	coal	gas	nuclear	solar low technical change	solar high technical change	wind low technical change	wind high technical change
First period (2011)	38	53	55	230	230	112	112
Second period (2035)	38	53	55	230	116	112	64

Table XXII: Generation costs estimation for scenarios

Orders of magnitude for kW costs for technologies were taken from WEO (IEA, 2012b).

Technology costs (€/kW)	coal	gas	nuclear	solar low technical change	solar high technical change	wind low technical change	wind high technical change
First period (2011)	1500	500	3000	3000	3000	3000	3000
Second period (2035)	1500	500	3000	3000	2000	3000	2000

Table XXIII: Installation costs estimation for scenarios

Moderate pro-nuclear policy consists in allowing nuclear investments, contrary to the current stance of Germany, Italy and Spain. Strong pro-nuclear policy adds an incentive for nuclear technology. Since the considered scenarios are the most favorable ones for future nuclear reactors, we considered potential change of nuclear stance in currently anti-nuclear countries for the second period (2025-2040): moderate pro-nuclear policy in Germany, and both moderate and strong pro-nuclear policy in Italy and Spain.

[26] Since fuel costs per MWh are not available in WEO, the fuel costs of the NEA report were kept, which constitutes a limit in cost calculation accuracy.

The following paragraph displays the results of the model in terms of technology preference company by company, country by country in the three scenarios, and assessed results on electricity mix.

3.2 Climate constraint scenario: moderately pro-nuclear case

FRANCE

	EDF	
2010-2025		
	wind	0,65
	solar	0,59
	nuclear	0,52
	gas	0,50
	coal	0,43
2025-2040		
	wind	0,54
	nuclear	0,49
	gas	0,48
	coal	0,45
	solar	0,43

Table XXIV: Technology preferences by company in French context

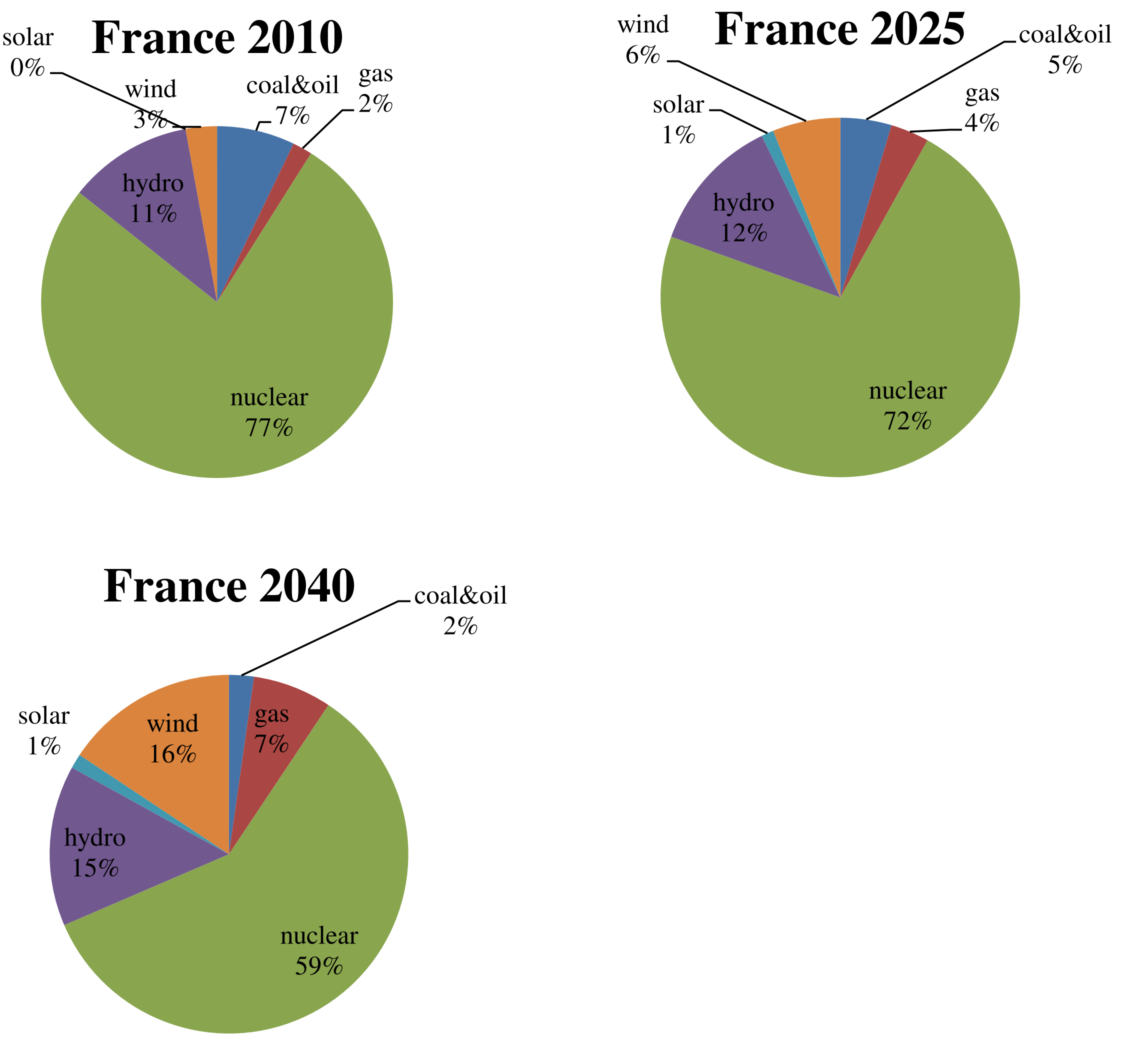


Figure 8: Generation mix evolution in France

GERMANY	EnWB		EOn		RWE		Vattenfall	
2010-2025								
	wind	0,50	wind	0,54	wind	0,54	wind	0,51
	solar	0,48	solar	0,52	solar	0,51	solar	0,49
	gas	0,34	gas	0,40	gas	0,39	gas	0,37
	coal	0,28	coal	0,32	coal	0,33	coal	0,29
2025-2040								
	wind	0,40	wind	0,44	wind	0,44	wind	0,41
	solar	0,37	solar	0,42	solar	0,41	solar	0,39
	gas	0,33	gas	0,39	gas	0,38	gas	0,36
	nuclear	0,33	nuclear	0,36	nuclear	0,35	nuclear	0,33
	coal	0,26	coal	0,30	coal	0,31	coal	0,28

Table XXV: Technology preferences by company in German context

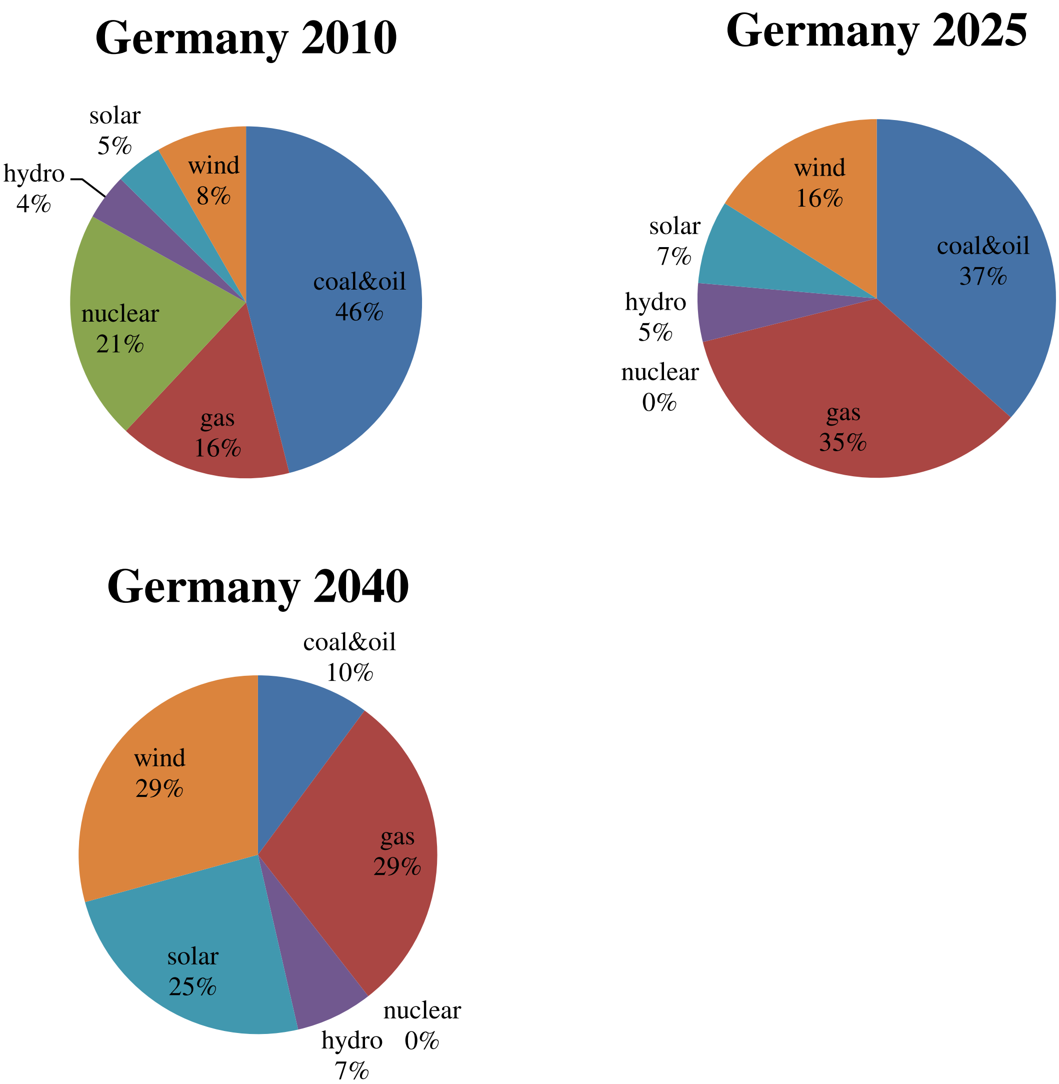


Figure 9: Generation mix evolution in Germany

ITALY

	Enel		Eni		EDF		EOn	
2010-2025	wind	0,57	wind	0,51	wind	0,64	wind	0,54
	solar	0,54	solar	0,49	solar	0,61	solar	0,51
	gas	0,43	gas	0,40	gas	0,48	gas	0,39
	coal	0,34	coal	0,27	coal	0,40	coal	0,31
2025-2040	wind	0,46	gas	0,43	wind	0,53	wind	0,43
	solar	0,43	wind	0,40	solar	0,50	gas	0,43
	gas	0,43	solar	0,38	nuclear	0,48	solar	0,40
	nuclear	0,37	nuclear	0,31	gas	0,43	nuclear	0,36
	coal	0,34	coal	0,27	coal	0,39	coal	0,31

Table XXVI: : Technology preferences by company in Italian context

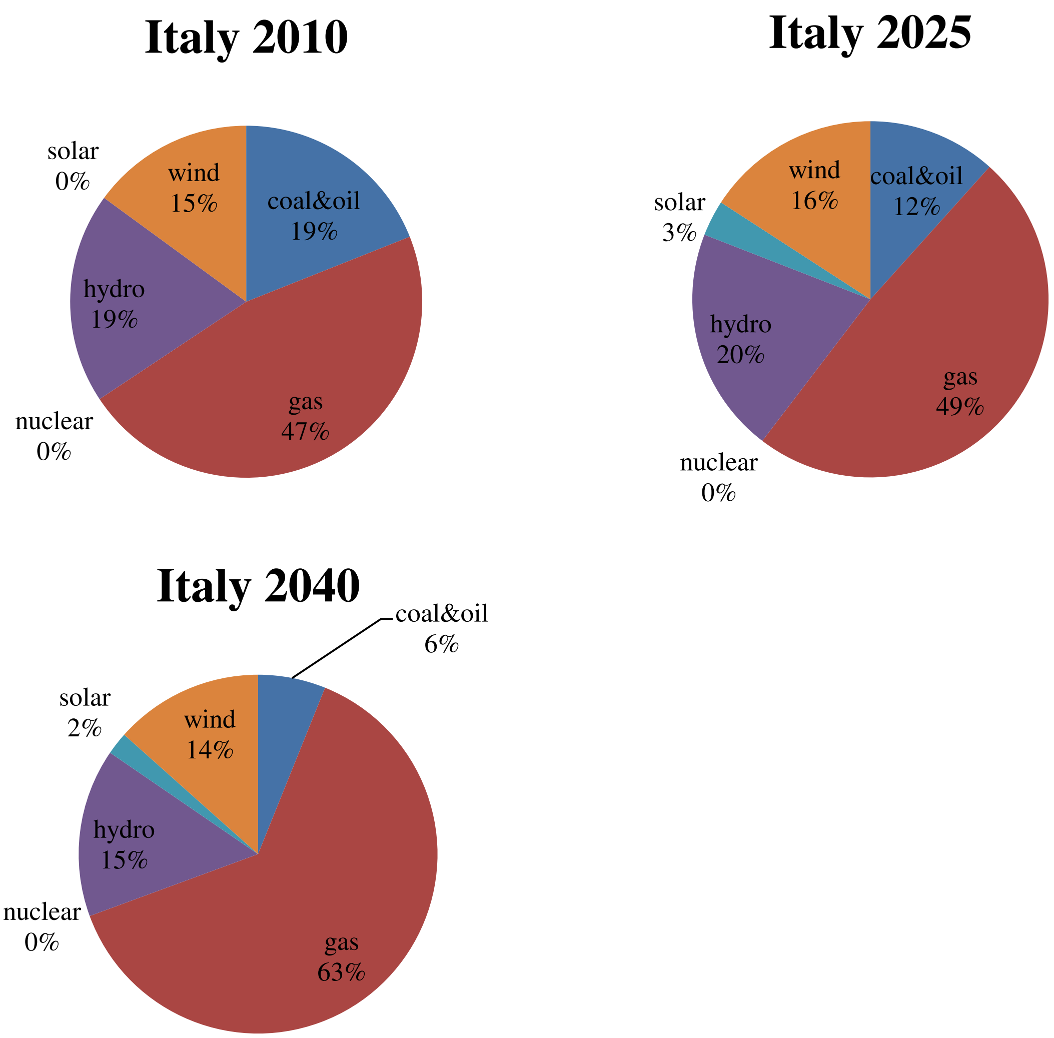


Figure 10: Generation mix evolution in Italy

SPAIN

	Endesa		Iberdrola		EDP		Gas Natural Fenosa		EOn	
2010-2025										
	wind	0,50	wind	0,51	wind	0,49	wind	0,48	wind	0,53
	solar	0,47	solar	0,48	solar	0,45	solar	0,45	solar	0,50
	gas	0,35	gas	0,38	gas	0,33	gas	0,37	gas	0,39
	coal	0,32	coal	0,29	coal	0,27	coal	0,26	coal	0,33
2025-2040										
	wind	0,40	wind	0,41	wind	0,39	wind	0,38	wind	0,43
	solar	0,37	solar	0,38	solar	0,36	gas	0,36	solar	0,40
	gas	0,34	gas	0,37	gas	0,32	solar	0,35	nuclear	0,42
	nuclear	0,32	nuclear	0,32	nuclear	0,28	nuclear	0,29	gas	0,38
	coal	0,30	coal	0,27	coal	0,25	coal	0,24	coal	0,31

Table XXVII: : Technology preferences by company in Spanish context

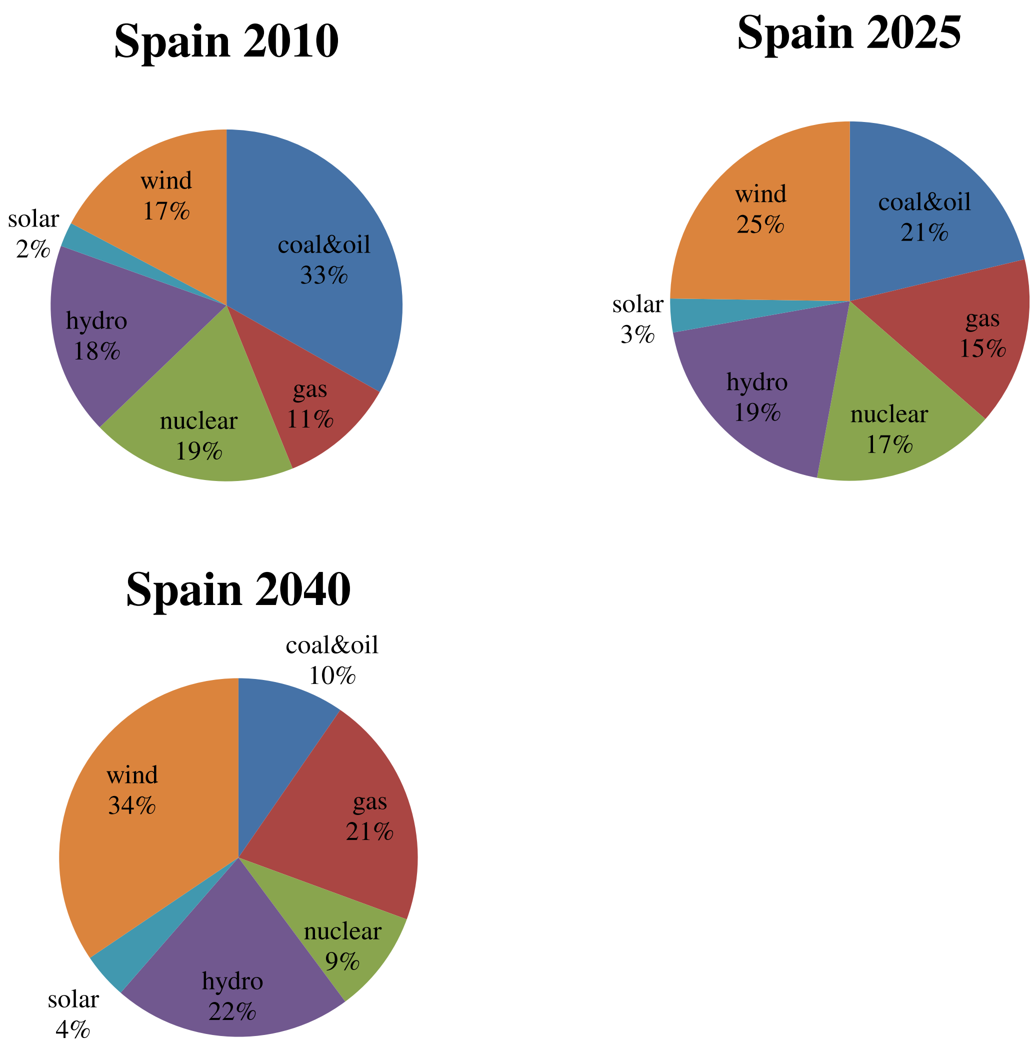


Figure 11: Generation mix evolution in Spain

UNITED KINGDOM

	Centrica		SSE		EDF		EOn		Iberdrola		RWE	
2010-2025												
	wind	0,47	wind	0,49	wind	0,63	wind	0,54	wind	0,51	wind	0,53
	solar	0,45	solar	0,46	solar	0,61	solar	0,51	solar	0,47	solar	0,50
	gas	0,36	gas	0,38	nuclear	0,51	gas	0,40	gas	0,37	gas	0,38
	nuclear	0,32	nuclear	0,31	gas	0,49	nuclear	0,38	nuclear	0,33	nuclear	0,36
	coal	0,25	coal	0,27	coal	0,42	coal	0,33	coal	0,28	coal	0,34
2025-2040												
	wind	0,37	wind	0,39	wind	0,53	wind	0,43	wind	0,41	wind	0,43
	solar	0,35	gas	0,37	solar	0,51	solar	0,41	solar	0,37	solar	0,40
	gas	0,35	solar	0,36	nuclear	0,51	gas	0,39	gas	0,36	gas	0,37
	nuclear	0,32	nuclear	0,31	gas	0,48	nuclear	0,38	nuclear	0,33	nuclear	0,36
	coal	0,23	coal	0,25	coal	0,40	coal	0,31	coal	0,26	coal	0,32

Table XXVIII: : Technology preferences by company in UK context

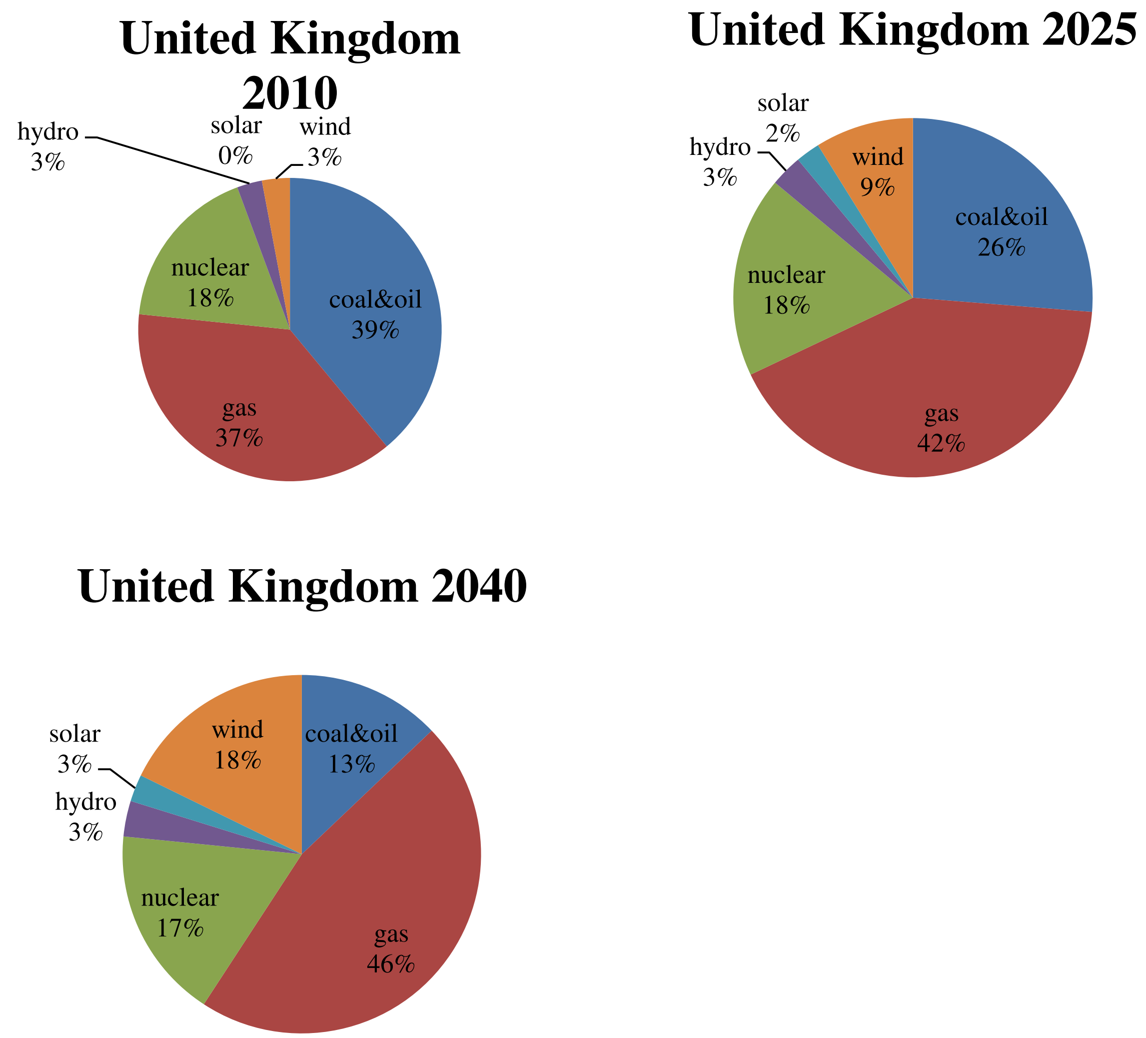


Figure 12: Generation mix evolution in United Kindgom

3.3 Climate constraint scenario: strongly pro-nuclear case

FRANCE		
	EDF	
2010-2025		
	wind	0,65
	solar	0,59
	nuclear	0,57
	gas	0,50
	coal	0,43
2025-2040		
	nuclear	0,57
	wind	0,54
	gas	0,48
	coal	0,45
	solar	0,43

Table XXIX: Technology preferences by company in French context

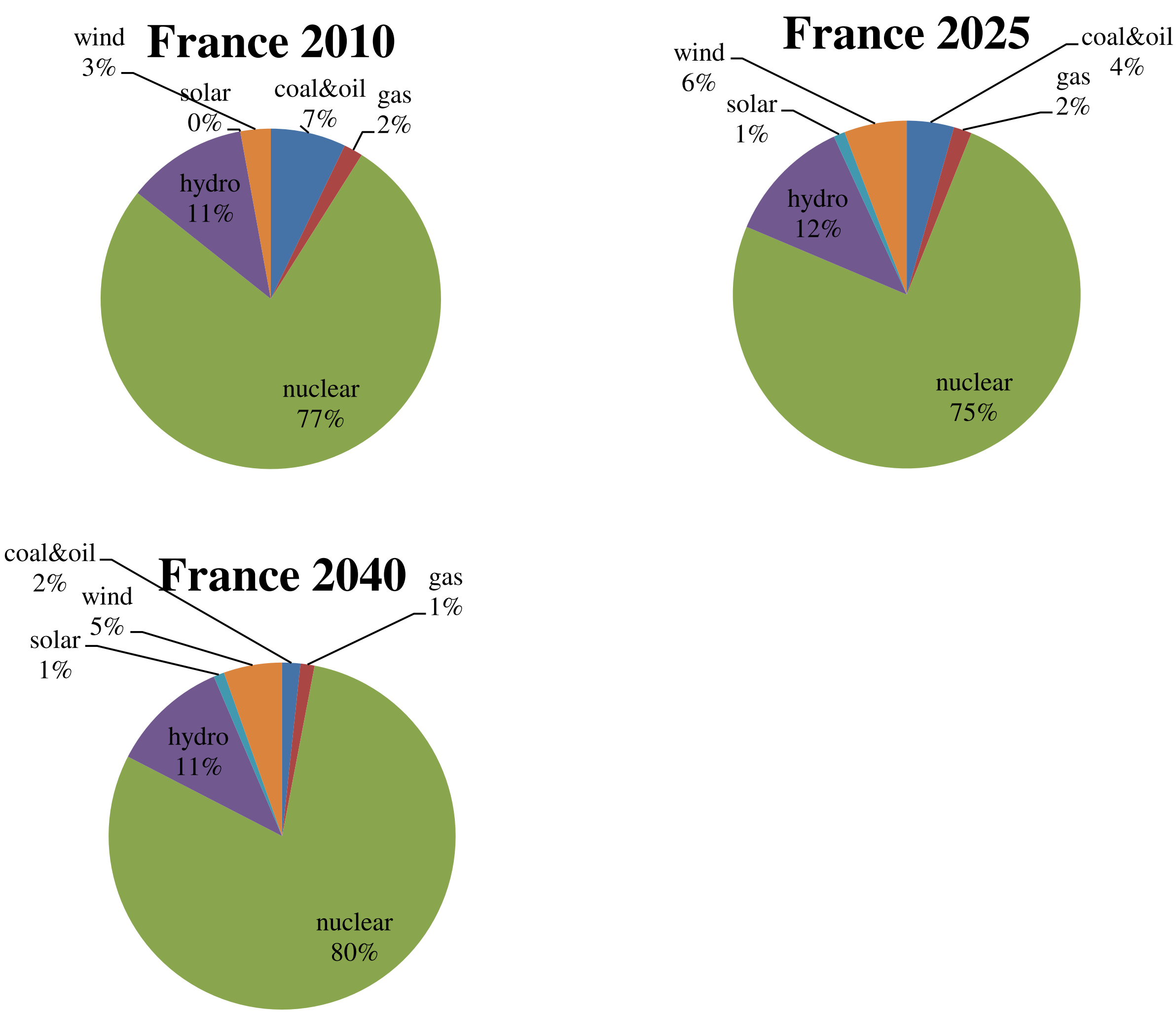


Figure 13: Generation mix evolution in France

GERMANY

	EnWB		EOn		RWE		Vattenfall	
2010-2025	wind	0,50	wind	0,54	wind	0,54	wind	0,51
	solar	0,48	solar	0,52	solar	0,51	solar	0,49
	gas	0,34	gas	0,40	gas	0,39	gas	0,37
	coal	0,28	coal	0,32	coal	0,33	coal	0,29
2025-2040	wind	0,40	wind	0,44	wind	0,44	wind	0,41
	solar	0,37	solar	0,42	solar	0,41	solar	0,39
	gas	0,33	gas	0,39	gas	0,38	gas	0,36
	nuclear	0,33	nuclear	0,36	nuclear	0,35	nuclear	0,33
	coal	0,26	coal	0,30	coal	0,31	coal	0,28

Table XXX: Technology preferences by company in German context

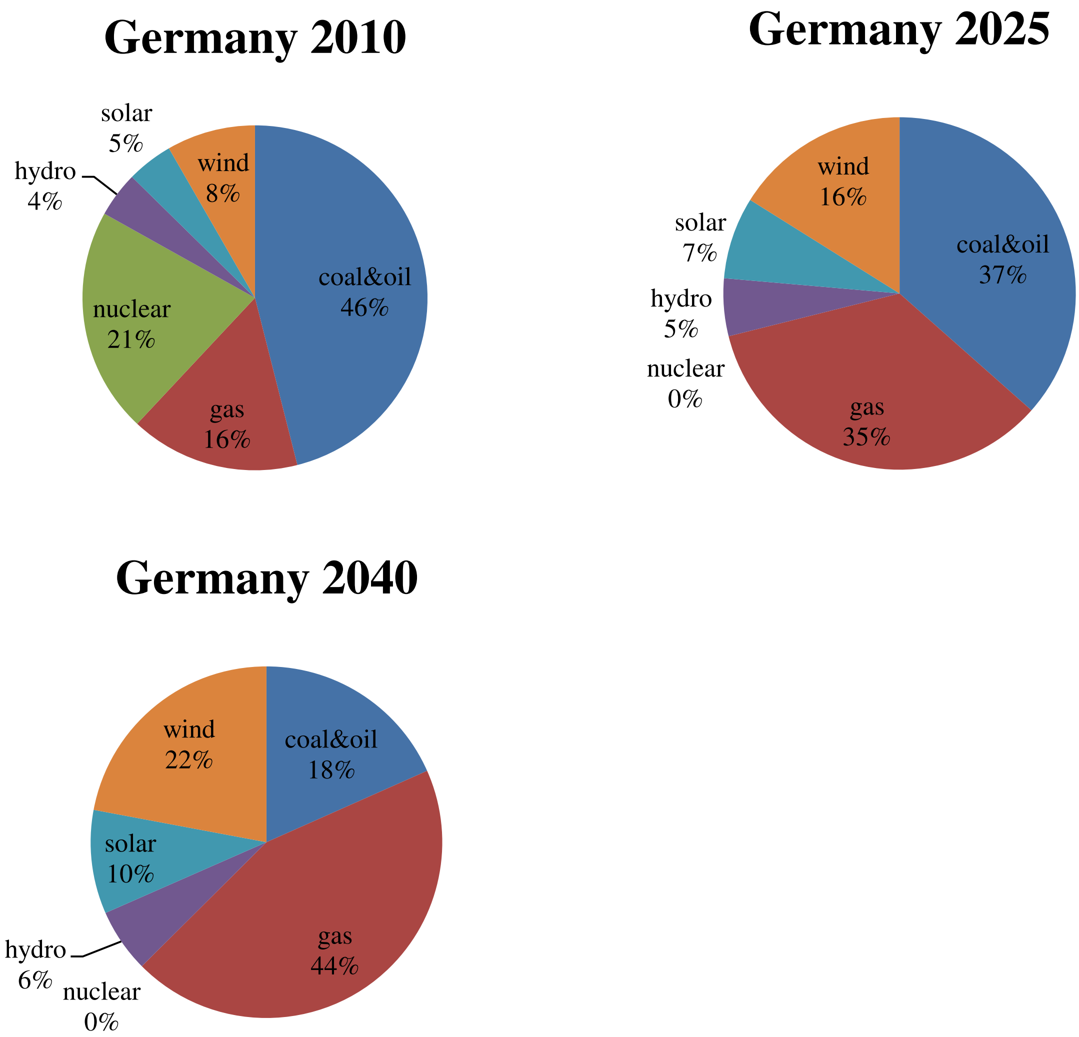


Figure 14: Generation mix evolution in Germany

ITALY

	Enel		Eni		EDF		EOn	
2010-2025	wind	0,56652	wind	0,510361	wind	0,635059	wind	0,539828
	solar	0,54	solar	0,49	solar	0,61	solar	0,51
	gas	0,43	gas	0,40	gas	0,48	gas	0,39
	coal	0,34	coal	0,27	coal	0,40	coal	0,31
2025-2040								
	wind	0,46	gas	0,43	wind	0,53	wind	0,43
	solar	0,43	wind	0,40	nuclear	0,53	gas	0,43
	gas	0,43	solar	0,38	solar	0,50	solar	0,40
	nuclear	0,42	nuclear	0,36	gas	0,43	nuclear	0,40
	coal	0,34	coal	0,27	coal	0,39	coal	0,31

Table XXXI: Technology preferences by company in Italian context

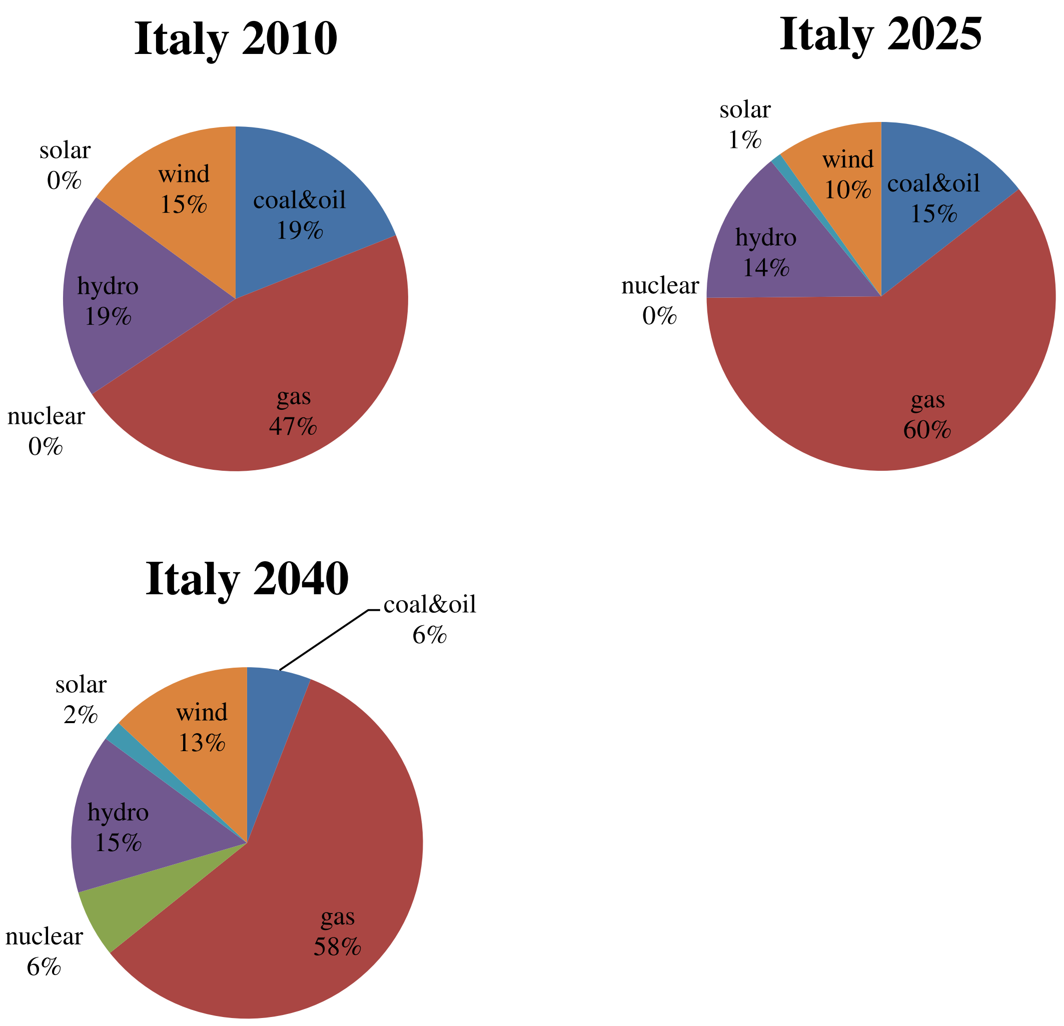


Figure 15: Generation mix evolution in Italy

SPAIN

	Endesa		Iberdrola		EDP		Gas Natural Fenosa		EOn	
2010-2025	wind	0,50	wind	0,51	wind	0,49	wind	0,48	wind	0,53
	solar	0,47	solar	0,48	solar	0,45	solar	0,45	solar	0,50
	gas	0,35	gas	0,38	gas	0,33	gas	0,37	gas	0,39
	coal	0,32	coal	0,29	coal	0,27	coal	0,26	coal	0,33
2025-2040	wind	0,40	wind	0,41	wind	0,39	wind	0,38	wind	0,43
	solar	0,37	solar	0,38	solar	0,36	gas	0,36	solar	0,40
	nuclear	0,39	nuclear	0,38	nuclear	0,35	nuclear	0,36	nuclear	0,42
	gas	0,34	gas	0,37	gas	0,32	solar	0,35	gas	0,38
	coal	0,30	coal	0,27	coal	0,25	coal	0,24	coal	0,31

Table XXXII: Technology preferences by company in Spanish context

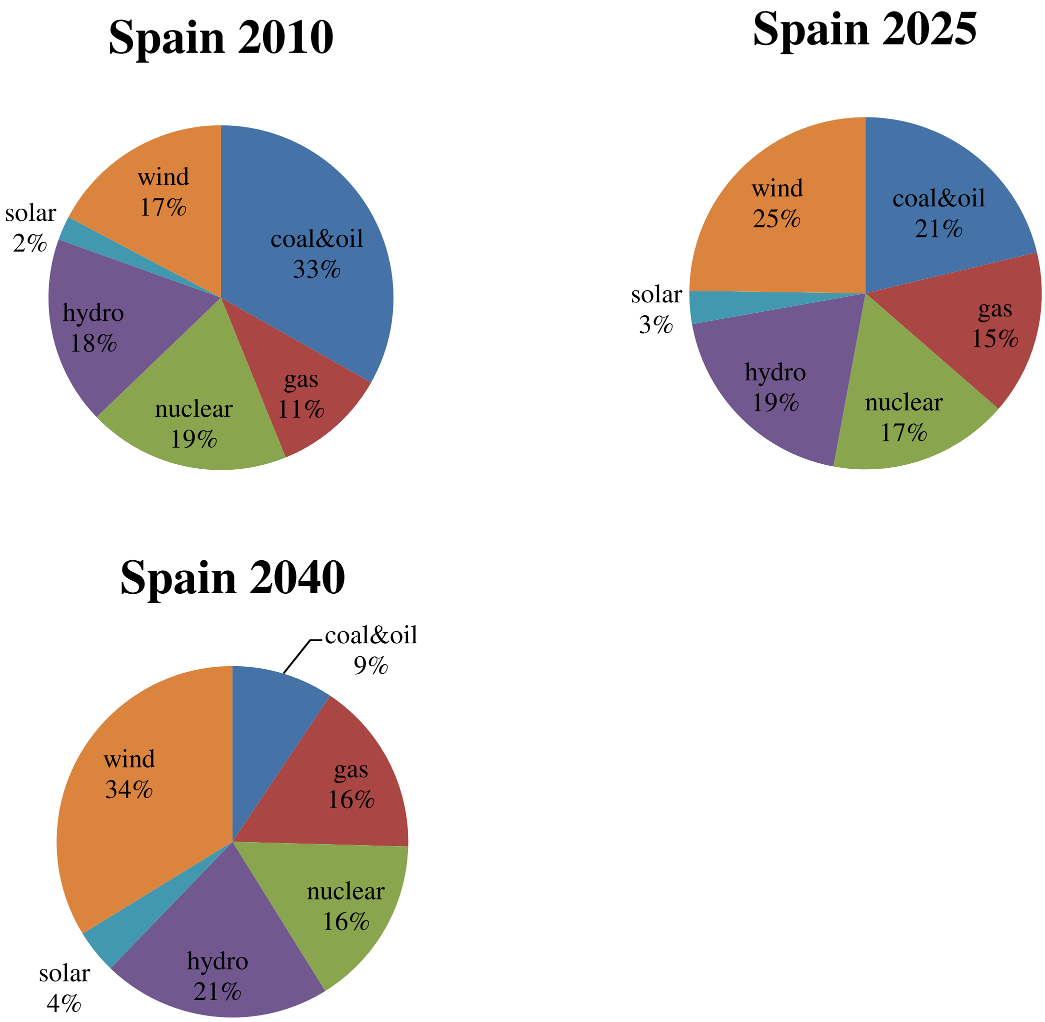
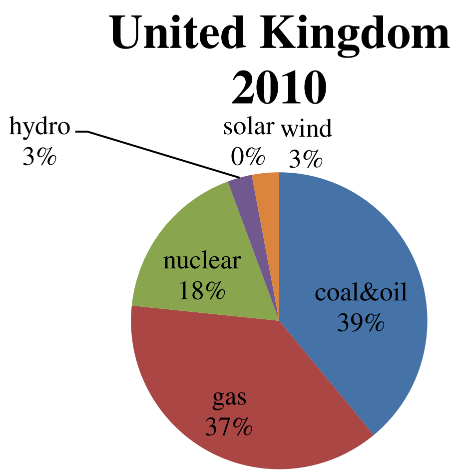


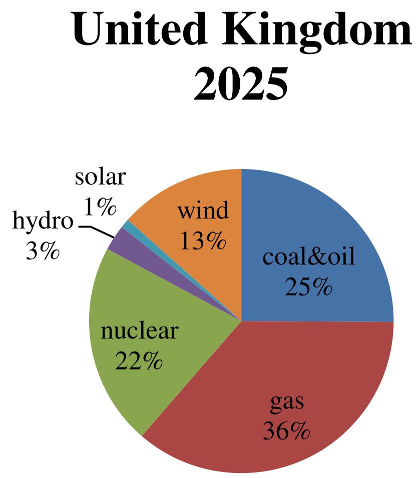
Figure 16: Generation mix evolution in Italy

UNITED KINGDOM

	Centrica		SSE		EDF		EOn		Iberdrola		RWE	
2010-2025												
	wind	0,47	wind	0,49	wind	0,63	wind	0,54	wind	0,51	wind	0,53
	solar	0,45	solar	0,46	solar	0,61	solar	0,51	solar	0,47	solar	0,50
	nuclear	0,37	gas	0,38	nuclear	0,56	nuclear	0,42	nuclear	0,38	nuclear	0,41
	gas	0,36	nuclear	0,36	gas	0,49	gas	0,40	gas	0,37	gas	0,38
	coal	0,25	coal	0,27	coal	0,42	coal	0,33	coal	0,28	coal	0,34
2025-2040												
	wind	0,37	wind	0,39	nuclear	0,55	wind	0,43	wind	0,41	wind	0,43
	nuclear	0,37	gas	0,37	wind	0,53	nuclear	0,42	nuclear	0,38	nuclear	0,41
	solar	0,35	nuclear	0,36	solar	0,51	solar	0,41	solar	0,37	solar	0,40
	gas	0,35	solar	0,36	gas	0,48	gas	0,39	gas	0,36	gas	0,37
	coal	0,23	coal	0,25	coal	0,40	coal	0,31	coal	0,26	coal	0,32

Table XXXIII: Technology preferences by company in UK context





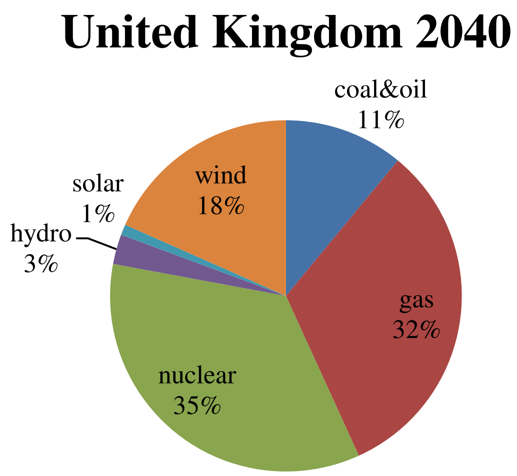


Figure 17: Generation mix evolution in United Kingdom

3.4 Totally green scenario: strongly pro-nuclear case

FRANCE	EDF	
2010-2025		
	wind	0,65
	solar	0,59
	nuclear	0,57
	gas	0,50
	coal	0,43
2025-2040		
	nuclear	0,57
	wind	0,56
	gas	0,49
	solar	0,47
	coal	0,44

Table XXXIV: Technology preferences by company in French context

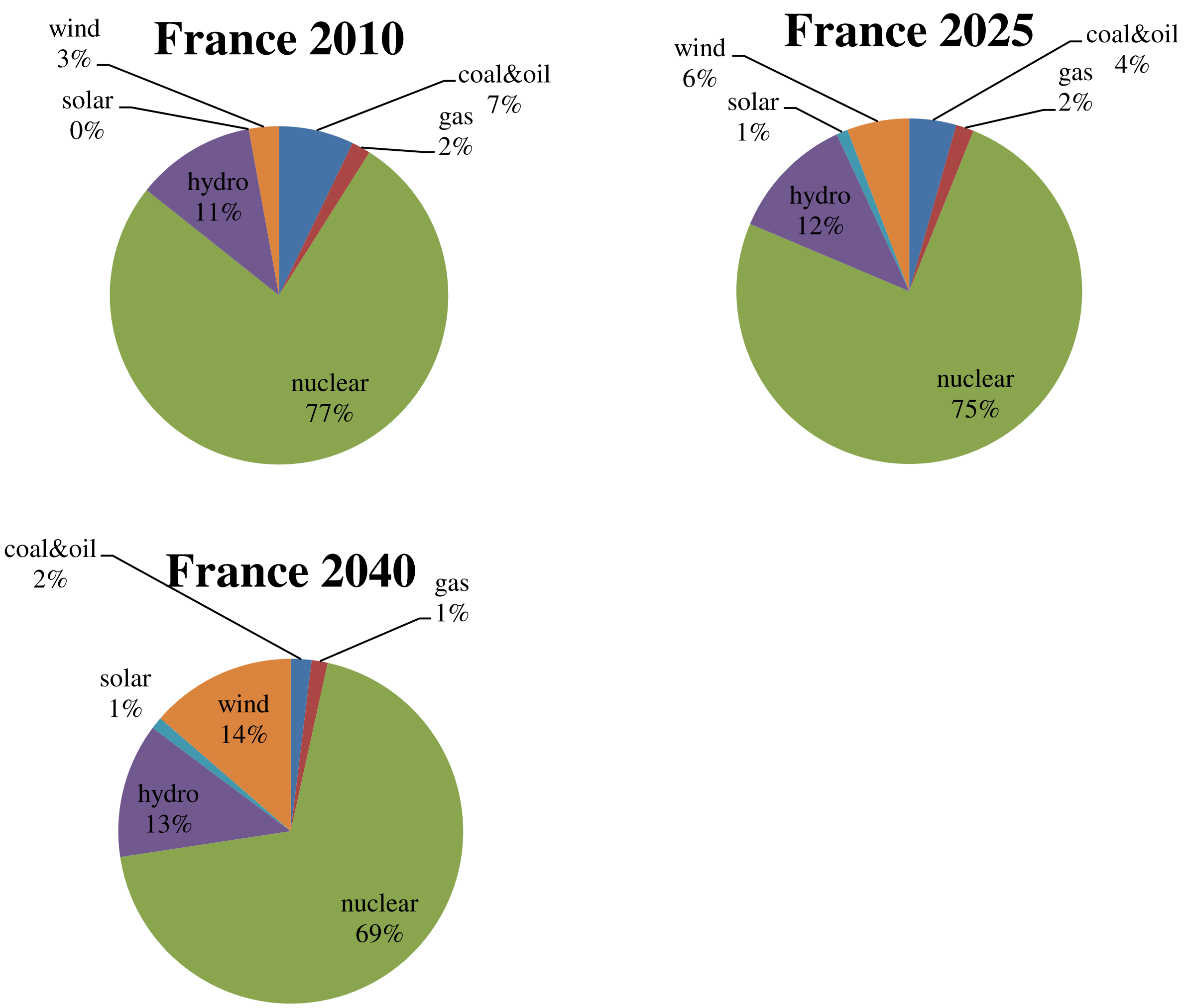


Figure 18: Generation mix evolution in France

GERMANY

	EnWB		EOn		RWE		Vattenfall	
2010-2025								
	wind	0,50	wind	0,54	wind	0,54	wind	0,51
	solar	0,48	solar	0,52	solar	0,51	solar	0,49
	gas	0,34	gas	0,40	gas	0,39	gas	0,37
	coal	0,28	coal	0,32	coal	0,33	coal	0,29
2025-2040								
	wind	0,41	wind	0,46	wind	0,45	wind	0,43
	solar	0,40	solar	0,44	solar	0,44	solar	0,41
	gas	0,33	gas	0,39	gas	0,38	gas	0,36
	nuclear	0,33	nuclear	0,36	nuclear	0,35	nuclear	0,33
	coal	0,26	coal	0,30	coal	0,31	coal	0,28

Table XXXV: Technology preferences by company in German context

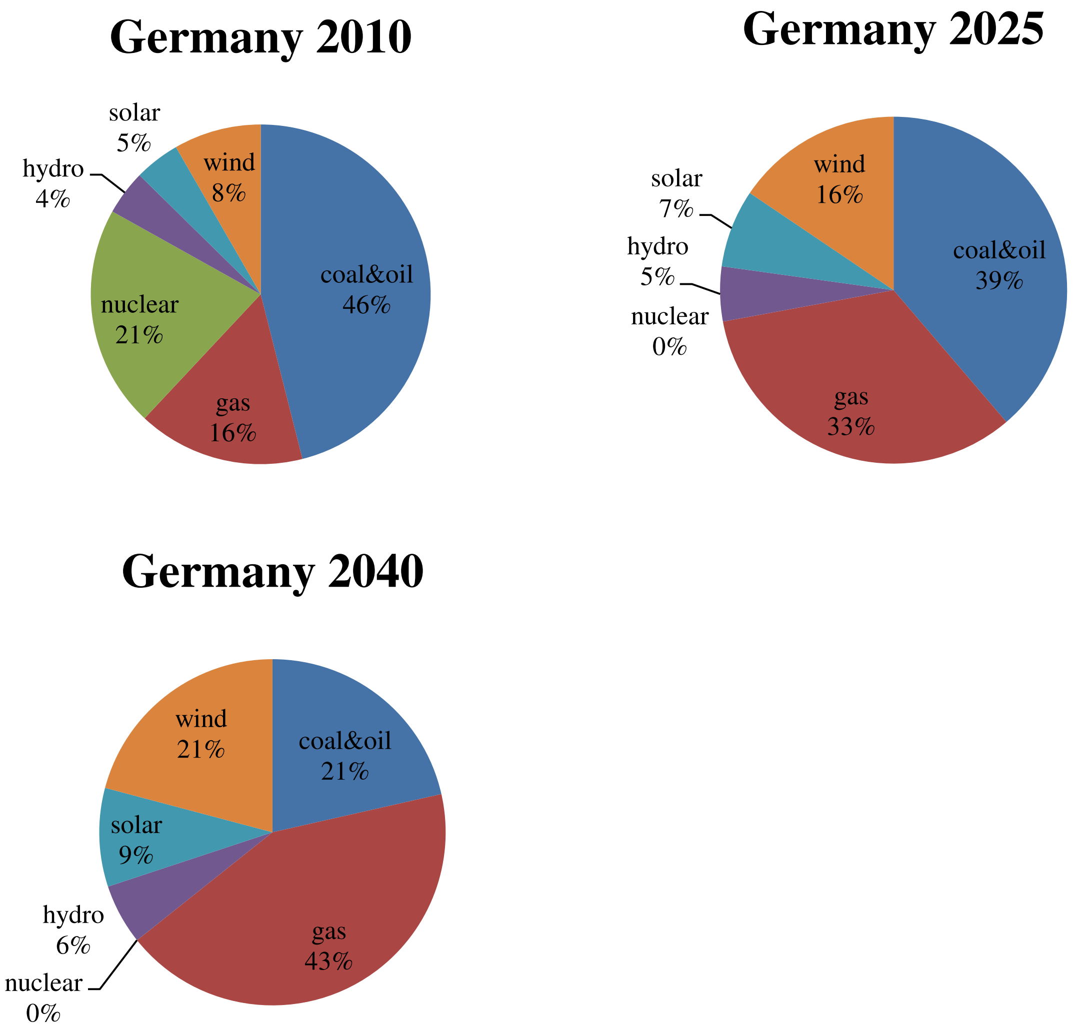


Figure 19: Generation mix evolution in Germany

ITALY

	Enel		Eni		EDF		EOn	
2010-2025								
	wind	0,57	wind	0,51	wind	0,64	wind	0,54
	solar	0,54	solar	0,49	solar	0,61	solar	0,51
	gas	0,43	gas	0,40	gas	0,48	gas	0,39
	coal	0,34	coal	0,27	coal	0,40	coal	0,31
2025-2040								
	wind	0,47	wind	0,42	nuclear	0,56	wind	0,45
	solar	0,46	solar	0,40	wind	0,54	solar	0,43
	nuclear	0,45	nuclear	0,39	solar	0,53	nuclear	0,43
	gas	0,42	gas	0,39	gas	0,47	gas	0,38
	coal	0,34	coal	0,27	coal	0,39	coal	0,31

Table XXXVI: Technology preferences by company in Italian context

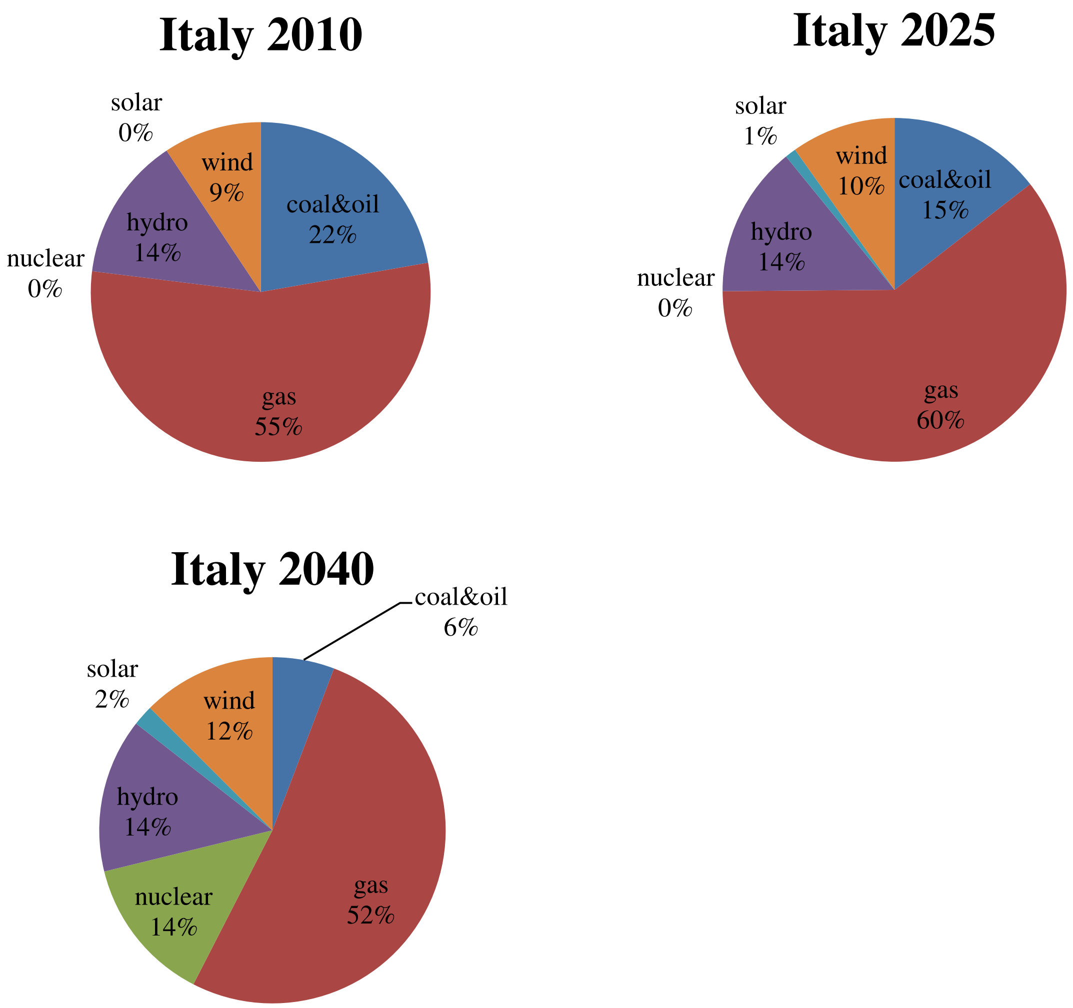


Figure 20: Generation mix evolution in Italy

SPAIN

	Endesa		Iberdrola		EDP		Gas Natural Fenosa		EOn	
2010-2025										
	wind	0,50	wind	0,51	wind	0,49	wind	0,48	wind	0,53
	solar	0,47	solar	0,48	solar	0,45	solar	0,45	solar	0,50
	gas	0,35	gas	0,38	gas	0,33	gas	0,37	gas	0,39
	coal	0,32	coal	0,29	coal	0,27	coal	0,26	coal	0,33
2025-2040										
	wind	0,42	wind	0,43	wind	0,42	wind	0,40	wind	0,42
	solar	0,41	solar	0,41	solar	0,40	solar	0,38	solar	0,41
	nuclear	0,39	nuclear	0,38	nuclear	0,36	gas	0,36	nuclear	0,39
	gas	0,34	gas	0,37	gas	0,33	nuclear	0,35	gas	0,34
	coal	0,28	coal	0,25	coal	0,24	coal	0,22	coal	0,28

Table XXXVII: Technology preferences by company in Spanish context

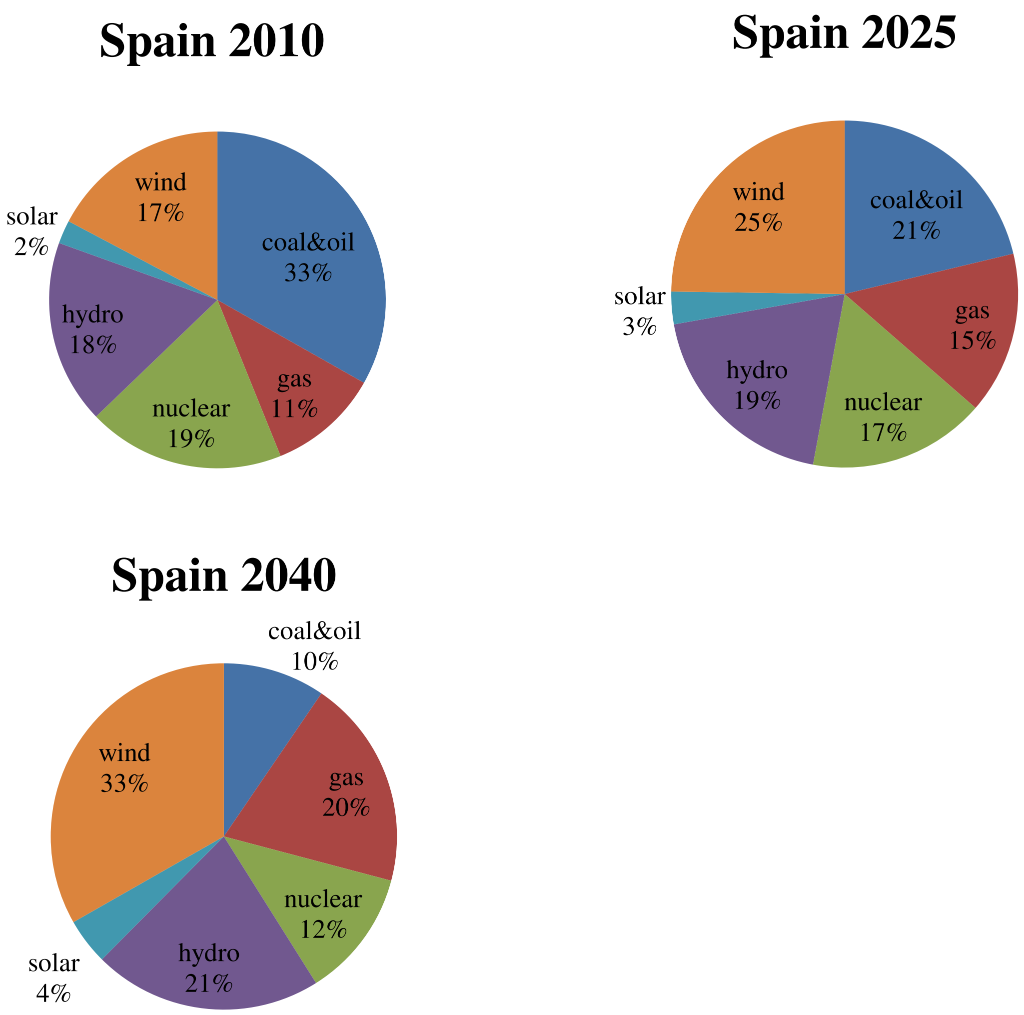


Figure 21: Generation mix evolution in Spain

UNITED KINGDOM

	Centrica		SSE		EDF		EOn		Iberdrola		RWE	
2010-2025												
	wind	0,47	wind	0,49	wind	0,63	wind	0,54	wind	0,51	wind	0,53
	solar	0,45	solar	0,46	solar	0,61	solar	0,51	solar	0,47	solar	0,50
	nuclear	0,37	gas	0,38	nuclear	0,56	nuclear	0,42	nuclear	0,38	nuclear	0,41
	gas	0,36	nuclear	0,36	gas	0,49	gas	0,40	gas	0,37	gas	0,38
	coal	0,25	coal	0,27	coal	0,42	coal	0,33	coal	0,28	coal	0,34
2025-2040												
	wind	0,39	wind	0,40	wind	0,55	wind	0,45	wind	0,42	wind	0,44
	solar	0,37	solar	0,39	nuclear	0,55	solar	0,43	solar	0,40	solar	0,43
	nuclear	0,37	gas	0,37	solar	0,53	nuclear	0,42	nuclear	0,38	nuclear	0,41
	gas	0,35	nuclear	0,36	gas	0,48	gas	0,39	gas	0,36	gas	0,37
	coal	0,23	coal	0,25	coal	0,40	coal	0,31	coal	0,26	coal	0,32

Table XXXVIII: Technology preferences by company in UK context

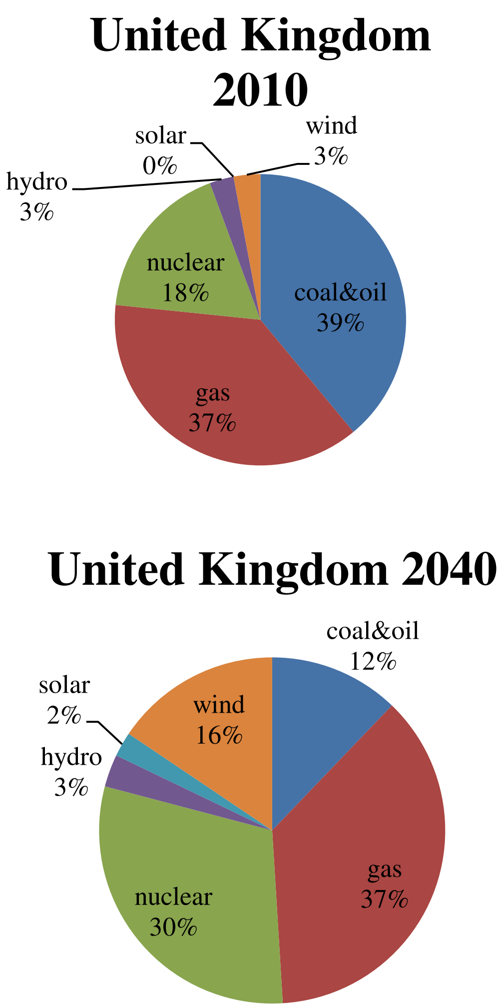


Figure 22: Generation mix evolution in United Kingdom

3.5 Discussion of results and perspectives for Generation IV

The values for compatibility index range approximately from 0.20 to 0.70, which means that only 50% of the possible range (from 0 to 1) is covered. This concentration of values is the consequence of a much aggregated index with numerous components. Trends in preferences can nevertheless be identified.

The most striking result of the technology preferences conveyed by the compatibility index is the huge preference for wind in most companies and most contexts. However, the index is pretty sensitive to plant size for small capacities and in the case of wind, increasing the 'size of plant' driver usually reduces the index to the level of the second preferred technology after approximately 1GW. This means that only the first installed GW really corresponds to an index superior to other technologies. The same tendency can be observed to a lesser extent for solar. This shows that in the end, the characteristic size of plant is more critical than kW cost or MWh cost: companies are attracted to small sized investments because they represent little risk. One can sense from this result that, as a consequence, Small Modular Reactors could have a better compatibility index than large-scale nuclear with most companies, and thus represent a very attractive development for the future of nuclear energy. SMR's higher costs due to little economies of scale could lessen this effect, but the present results on solar for instance allow thinking that it would still be below current compatibility index values for nuclear.

Moreover, despite various profiles of companies, the ranking in preferred technologies is not so different from one company to another: wind is mostly the favorite while coal is mostly the least favorite. Except for companies with an extreme profile in technology repartition such as EDF (mostly generation from nuclear) or Eni (mostly generation from gas), specificities of the company's generation mix are not so visible in choices. Indicators of the size of the company (installed capacity, revenue, amount of generated electricity) will favor all investment and thus increase compatibility index for all technologies, but not change the order of preferred technologies: the differences would rather be significant when comparing compatibility index of one technology for two companies of very different sizes.

Unsurprisingly in such scenarios of strong climate policy, coal is the least preferred technology in most cases. However, lowering carbon price to the minimum does not change spectacularly the preference for this technology: the index is significantly increased, but coal is still at the bottom of the ranking, as we can see with the example of RWE in Germany, which is a favorable case for coal (important coal share in the mix).

wind	0,44
solar	0,41
gas	0,38
nuclear	0,35
coal	0,31

Table XXXIX: Technology preference for RWE in Germany in the Climate Constraint scenario with moderate pro-nuclear policy hypothesis (carbon price : €90/tCO_2)

wind	0,44
solar	0,41
gas	0,40
nuclear	0,35
coal	0,34

Table XL: Technology preference for RWE in Germany with minimum carbon price (€9/tCO2), all other things being equal

This result confirms the importance of plant size over costs in investment choices.

As expected, the most significant rise in nuclear share lies in the Climate Constraint scenario with strong pro-nuclear policy. High renewable technical progress combined to strong climate policy and strong pro-nuclear policy is more favorable to the development of nuclear than low technical progress of renewable combined to strong climate policy and moderate pro-nuclear policy. This shows that according to our model, nuclear development is way more threatened by lack of policy incentive than by economic competitiveness of other technologies.

In the Climate Constraint scenario with moderately pro-nuclear policy, nuclear energy is only present in France and the United Kingdom, even with the hypothesis that a moderate pro-nuclear policy could appear in the three other countries. The declining yet still massive share of nuclear energy in the French generation mix allows thinking that SFR penetration is fully possible. The share in United Kingdom, though, stagnating around today's value, seems much less favorable.

The Climate Constraint scenario with strong pro-nuclear policy (i.e. a government incentive in favor of nuclear energy) is however the most favorable one to nuclear energy. The share of nuclear energy slightly increases even in France where nuclear energy becomes the favorite one during the second period; it doubles in United Kingdom. SFR penetration seems possible especially since both countries share nuclear operator EDF. The hypothesis for a change in nuclear stance of countries in the second period (2025-2040) shows that with a government incentive, there is a potential for nuclear to penetrate again the Italian market and to reinvest the Spanish market and maintain the nuclear share on it. Such recent return to nuclear would probably make it difficult to implement a new technology such as SFR so soon though.

The Totally Green scenario with strong pro-nuclear policy shows a slight drop in the French nuclear share, but still very encouraging prospects in United Kingdom, Spain and Italy. The perspectives for SFR penetration are similar to the Climate Constraint scenario with strong pro-nuclear policy.

4 Conclusion

A value creation approach combined to Design Structure Matrix and Quality Function Development Matrix methods has allowed building a tool replicating the behaviors of investors. Technology choices were thus modeled for the companies in the scope under study and in the three scenarios retained by structural analysis. It shows that future nuclear development is even more bonded to state support than sensed in Chapter 2. Even with strong climate policy and no cost reduction of other technologies, without incentives from national governments, nuclear energy seems to see its share decreasing with little prospects of stepping into the next generation of nuclear reactors. Wind is widely adopted coal share declines in all scenarios.

This approach has the advantage of offering a tool taking into account all identified drivers to assess a company’s choice of technology. It can be adapted to other contexts by adapting the weights of corresponding drivers of even by adding drivers to the matrix following the same method. However it has limits since it is much aggregated and does not give very contrasted results. Moreover, the approach keeps the same companies’ profiles over three decades, which does allow to model potential concentration movements, change of market share, and does not take into account the change in their generation mix due to the modeled investments.

Lastly, this chapter gives the preferences of companies regarding technologies, but yet the question remains of the preference for SFR over the current LWR technology. The next chapter focuses on both technologies in order to address the issue in an exclusively nuclear context.

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6 Annexes

6.1 Company characteristics

Sources: Power Companies Annual Reports, 2011

6.1.1 France

Company	Électricité de France
Revenue (G€)	6530,0%
Shareholding Structure	Etat à 84.4% Employees 1.84% Free floating2.82% Auto 0.06% Institutionals France 3.07% Institutionals Europe 4.7% Institutionals out of EU 3.06%
Installed Capacity GW	139,50
Total Generation TWh	628,20
nuclear	79,6%
coal and oil	8,2%
gas	4,8%
hydro	5,9%
wind	1,0%
solar PV	0,1%

Table XLI: Power Companies in France

6.1.2 Germany

Company	EnWB	EON
Revenue (G€)	18,8	112
Shareholding Structure	OEW (Baden Würtenberg authorities) 46.55% NECKARPRI-Beteiligungsgesellschaft mbH (Land Baden Würtenberg) 46.55% auto 2.30% Free floating0.40% Badische Energieaktionärs-Vereinigung (BEV) 2.45% Gemeindeelektrizitätsverband Schwarzwald-Donau (G.S.D.) 0.95% Landeselektrizitätsverband Württemberg (LEVW) 0.11% Neckar-Elektrizitätsverband (NEV) 0.69%	21 % Free floating(retail investors) 79 % institutionnels (35% German shareholders)
Installed Capacity GW	13,4	19,6
Total Generation TWh	64	195,34
nuclear	51,0%	31,2%
coal and oil	34,5%	33,7%
gas		22,6%
hydro	1,5%	7,4%
wind	0,9%	5,0%
solar	3,4%	0,0%
biomass/biogas	4,7%	0,1%

Company	RWE	Vattenfall
Revenue (G€)	53	21,11
Shareholding Structure	Private shareholders 14% Own shares 5% Employee shareholders 1% BlackRock 3% RW Energie-Beteiligungsgesellschaft 16% Other institutional shareholders 61%	100% Swedish State
Installed Capacity GW	31,4	14,0
Total Generation TWh	225,3	166,7
nuclear	20,1%	25,5%
coal and oil	56,0%	43,5%
gas	19,0%	7,5%
hydro	1,0%	20,7%
wind	4,0%	2,0%
solar		0,0%
biomass/biogas		8,3%

Table XLII: Power Companies in Germany

6.1.3 Italy

Company	Enel	Edison	Eni
Revenue (G€)	79,51	12,03	109,59
Shareholding Structure	Italian Ministry of Economy and Finance 31.24% Institutional investor 40.3% Private investors 28.5%	EDF 99.5 %	Legal entities 50.60 % Block shareholders 30.30% Individual shareholders 9.36 % Treasury shares 9.55 % Major shareholders : Italian Ministry of Economy and Finance 3.93 % CdP (Caisse dépôts) 26.37% BNP 2.29 %
Installed Capacity GW	39,88	6,10	5,31
Total Generation TWh	293,90	33,16	25,23
nuclear	13,4%		
coal and oil	29,3%	81,9%	
gas	29,1%		almost 100%
hydro	23,9%	16,0%	
wind	2,1%	2,1%	
solar PV	0,0%		
other renewables	1,9%		

Table XLIII: Power Companies in Italy

6.1.4 Spain

Company	Endesa	Iberdrola	Gas Natural Fenosa
Revenue (G€)	32,686	31,648	21,076
Shareholding Structure	ENEL 92 %	ACS, Actividades de Construccion y servicios 18,8% Qatar investment authorithy 8,5 %	Criteria CaixaHolding 35 % Grupo Repsol 30% Inversores institucionales internacionales 17.2 % Accionistas individuales en España. 9.1 % Sonatrach 3.9 % Inversores institucionales españoles 3.0 % Caixa d'Estalvis de Catalunya. 1.5%
Installed Capacity GW	23,072	19,7	12,76
Total Generation TWh	75,132	145,126	56,354
nuclear	33,5%	16,7%	7,8%
charbon	58,3%	8,9%	7,9%
gas		42,3%	74,7%
hydro	8,2%	12,2%	5,3%
wind	0,0%	19,2%	4,2%
solar	0,0%	0,6%	
biomass biogas			
cogeneration and waste			

Company	EDP	EOn
Revenue (G€)	14,605	cf Germany
Shareholding Structure	China Three Gorge 21.35% Iberdrola 6.79 % Liberbank, S.A.5.1 % José de Mello Energia, S.A. 4.64 % PARPÚBLICA - Participações Públicas, SGPS, S.A. 4.14% SENFORA SARL 4.06 % Grupo BCP + Fundo de Pensões do Grupo BCP 3.36% Banco Espírito Santo, S.A. 2.45% Sonatrach 2.38 % Qatar Holding LLC 2.27% EDP (Treasury Stock) 0.89%	
Installed Capacity GW	6,087	
Total Generation TWh	58,393	
nuclear	2,1%	
charbon	21,0%	
gas	11,7%	
hydro	33,2%	
wind	28,7%	
solar	0,0%	
biomass biogas	0,3%	
cogeneration and waste	3,0%	

Table XLIV: Power Companies in Spain

6.1.5 United Kingdom

<table>
<tr><td>Company</td><td>Centrica Energy</td><td>Scottish and Southern Energy plc.</td><td>EDF Energy</td><td>E.On UK.</td><td>RWE Npowerc.</td><td>Scottish Power</td></tr>
<tr><td>Revenue G€</td><td>27,36</td><td>38,40</td><td rowspan="10">cf EDF France</td><td rowspan="10">cf Eon Germany</td><td rowspan="10">cf RWE Germany</td><td rowspan="10">cf Iberdrola Spain</td></tr>
<tr><td>Shareholding Structure</td><td>93% Institutionals
7% Free float</td><td></td></tr>
<tr><td>Installed Capacity</td><td>6,00</td><td>11,29</td></tr>
<tr><td>Total Generation TWh</td><td>26,70</td><td>46,00</td></tr>
<tr><td>nuclear</td><td>0,42</td><td></td></tr>
<tr><td>coal and oil</td><td></td><td>0,83</td></tr>
<tr><td>gas</td><td>0,56</td><td></td></tr>
<tr><td>hydro</td><td></td><td>0,17</td></tr>
<tr><td>wind</td><td>0,02</td><td></td></tr>
<tr><td>solar PV</td><td></td><td></td></tr>
</table>

Table XLV: Power Companies in United Kingdom

6.2 Decommissioning hypothesis

Retiring capacities until 2040 were estimated with the age of European power plants given in RWE Facts and Figures 2012.

Shut down in 2 periods	**Retirement %**	France	Germany	Italy	Spain	United Kingdom
	source: RWE					
Coal : 70%		14,23	51,59	11,19	11,36	29,84
2010-2025	*35%*	4,98	18,06	3,92	3,98	10,44
2025-2040	*35%*	4,98	18,06	3,92	3,98	10,44
Total capacity to replace		9,96	36,11	7,83	7,95	20,89
Oil : 85%		7,86	4,14	9,89	8,14	6
2010-2025	*50%*	3,93	2,07	4,95	4,07	3,00
2025-2040	*35%*	2,75	1,45	3,46	2,85	2,10
Total capacity to replace		6,68	3,52	8,41	6,92	5,10
Gas : 25%		0,56	23,12	51,86	6,28	34,62
2010-2025	*10%*	0,06	2,31	5,19	0,63	3,46
2025-2040	*15%*	0,08	3,47	7,78	0,94	5,19
Total capacity to replace		0,14	5,78	12,97	1,57	8,66
Hydro		25,21	11,03	21,52	18,54	4,39
2010-2025	NA: constant					
2025-2040	NA: constant					
Total capacity to replace						
Nuclear: 60%*		63,13	20,47	0	7,42	10,87
2010-2025	*20%*	12,63	20,47	0,00	1,48	2,17
2025-2040	*40%*	25,25		0,00	2,97	4,35
Total capacity to replace		37,88	20,47	0,00	4,45	6,52
**except for Germany : total shut down in first period*						
Solar/Wind/Geothermal		7,09	48,29	10,31	25,36	5,46
2010-2025	*0%*					
2025-2040	*0%*					

Table XLVI: Estimated retiring capacities per technology until 2040

Shut down per period (GW)	**France**	**Germany**	**Italy**	**Spain**	**United Kingdom**
2010-2025	21,6	42,9	14,0	10,2	19,1
2025-2040	33,1	23,0	15,2	10,7	22,1
Total GW capacity shut down	**54,7**	**65,9**	**29,2**	**20,9**	**41,2**

Table XLVII: Total estimated retiring capacities until 2040

6.3 Capacity mix evolution in scenarios

6.3.1 Climate constraint with moderate pro-nuclear policy

Technology	France			Germany			Italy		
	2010	2025	2040	2010	2025	2040	2010	2025	2040
coal&oil	17,8%	10,6%	4,4%	35,5%	22,7%	10,3%	19,8%	11,5%	4,5%
gas	4,5%	8,0%	14,0%	14,7%	25,7%	29,6%	48,7%	48,0%	47,2%
nuclear	50,8%	44,6%	30,9%	13,0%	0,0%	0,0%	0,0%	0,0%	0,0%
hydro	20,3%	20,3%	20,3%	7,0%	7,0%	7,0%	20,2%	20,2%	20,2%
solar	0,0%	3,9%	3,9%	15,4%	21,6%	24,6%	0,0%	3,2%	5,8%
wind	5,7%	11,3%	24,6%	15,4%	24,0%	29,6%	15,6%	15,6%	20,0%

Technology	Spain			United Kingdom		
	2010	2025	2040	2010	2025	2040
coal&oil	25,3%	14,9%	6,0%	38,4%	24,0%	10,5%
gas	8,1%	10,6%	13,1%	37,0%	38,1%	37,9%
nuclear	9,6%	7,7%	3,8%	11,6%	11,0%	9,5%
hydro	24,0%	24,0%	24,0%	4,7%	4,7%	4,7%
solar	6,6%	8,1%	10,0%	0,0%	7,7%	7,7%
wind	26,3%	34,6%	43,0%	5,8%	16,2%	29,0%

Table XLVIII: Capacity mix evolution in the Climate Constraint scenario with moderate pro-nuclear policy

6.3.2 Climate constraint with strong pro-nuclear policy

Technology	France			Germany			Italy		
	2010	2025	2040	2010	2025	2040	2010	2025	2040
coal&oil	17,8%	10,6%	4,4%	35,5%	22,7%	10,3%	19,8%	11,5%	4,5%
gas	4,5%	4,1%	3,4%	14,7%	25,7%	29,6%	48,7%	48,0%	45,0%
nuclear	50,8%	48,5%	54,8%	13,0%	0,0%	0,0%	0,0%	0,0%	3,2%
hydro	20,3%	20,3%	20,3%	7,0%	7,0%	7,0%	20,2%	20,2%	20,2%
solar	0,0%	3,9%	3,9%	15,4%	21,6%	24,6%	0,0%	3,2%	5,4%
wind	5,7%	11,3%	11,3%	15,4%	24,0%	29,6%	15,6%	15,6%	20,1%

Technology	Spain			United Kingdom		
	2010	2025	2040	2010	2025	2040
coal&oil	25,3%	14,9%	6,0%	38,4%	24,0%	9,3%
gas	8,1%	10,6%	10,3%	37,0%	34,6%	27,1%
nuclear	9,6%	7,7%	6,7%	11,6%	10,3%	19,5%
hydro	24,0%	24,0%	24,0%	4,7%	4,7%	4,7%
solar	6,6%	8,1%	10,0%	0,0%	3,6%	3,2%
wind	26,3%	34,6%	43,2%	5,8%	19,8%	30,9%

Table XLIX: Capacity mix evolution in the Climate Constraint scenario with strong pro-nuclear policy

6.3.3 Totally green with strong pro-nuclear policy

Technology	France			Germany			Italy		
	2010	2025	2040	2010	2025	2040	2010	2025	2040
coal&oil	17,8%	10,6%	4,4%	35,5%	24,9%	12,5%	19,8%	11,5%	4,5%
gas	4,5%	4,1%	3,4%	14,7%	25,7%	29,9%	48,7%	48,0%	40,7%
nuclear	50,8%	48,5%	41,5%	13,0%	0,0%	0,0%	0,0%	0,0%	7,1%
hydro	20,3%	20,3%	20,3%	7,0%	7,0%	7,0%	20,2%	20,2%	20,2%
solar	0,0%	3,9%	3,9%	15,4%	21,6%	24,7%	0,0%	3,2%	5,8%
wind	5,7%	11,3%	24,6%	15,4%	24,0%	29,1%	15,6%	15,6%	19,6%

Technology	Spain			United Kingdom		
	2010	2025	2040	2010	2025	2040
coal&oil	25,3%	14,9%	6,0%	38,4%	24,0%	10,5%
gas	8,1%	10,6%	12,3%	37,0%	35,6%	32,0%
nuclear	9,6%	7,7%	5,0%	11,6%	13,7%	17,4%
hydro	24,0%	24,0%	24,0%	4,7%	4,7%	4,7%
solar	6,6%	8,1%	10,5%	0,0%	3,6%	7,7%
wind	26,3%	34,6%	41,9%	5,8%	16,0%	27,0%

Table L: Capacity mix evolution in the Totally Green scenario with strong pro-nuclear policy

6.4 Load factors used for generation mix reconstitution

The load factors used to convert capacity mix to generation mix are not the theoretical ones used in the compatibility matrix and coming from the NEA report on power generation costs (OECD-NEA, 2010), since they show what the technology is capable of (which is essential for the investor's choice) but do not reflect how they are effectively used in the five countries under study. First, in this study, coal and fuel oil are treated together; since coal is a baseload capacity while fuel oil very flexible and used for peak, the average load factor for coal and fuel oil is thus more or less situated around 50% according to the respective share of coal and fuel oil. Moreover, the case of France is a little peculiar since due to their massive nuclear capacity, fossil fuel plants have even lower load factors as in other countries. Table LI below shows the used load factors for generation mix reconstitution.

Technology	Load factor
coal and fuel oil	20% in France 60% in Germany 50% in other countries
gas	20% in France 50% in other countries
nuclear	75%
hydro	28%
solar	13%
wind	25%

Table LI: Load factors (source: RTE)

Chapter 4: Economic value of R&D for fast reactors taking into account uncertainty on their competitiveness

A preliminary version of this paper was presented as a poster at the International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13) in March 2013 in Paris, France, and published in the proceedings under the title 'Why R&D for Generation IV reactors should be subsidised? A strictly economic point of view' (N. Taverdet-Popiolek, B. Shoai Tehrani); it was published as a working paper in Cahiers du Creden (Cahier N° 13.09.101) under the title 'Economic assessment of R&D with real options in the field of fast reactors taking into account uncertainty on their competitiveness: the case of France'(N. Taverdet-Popiolek, B. Shoai Tehrani).

It was also submitted to the review 'Revue économique' in July 2013 under the title 'Economic assessment of R&D with real options in the field of fast reactors taking into account uncertainty on their competitiveness: the case of France' (N. Taverdet-Popiolek, B. Shoai Tehrani).

In the previous chapters, we have studied the drivers for investment decision in new electricity generating capacities, in order to assess what could be the investment decisions when Generation IV Fast Reactors are ready to be deployed in 2040. We have sought to identify the drivers resulting from short-term opportunity behaviours in addition to the drivers that stem from long-term economic rationality. As said in the introduction, the study is based on the assumption that the French research program will have delivered properly by then. One step ahead of the investment decision for industrial deployment, another decision had thus to be made: the investment decision in a research program for this technology. In France this choice was made in 2012 with the decision to build the ASTRID prototype (Ministère du Développement durable 2013). As said earlier, Generation IV Fast Reactors make better use of natural uranium than Generation III Reactors, contribute to long-term waste management through using plutonium from thermal reactors' waste, recycling it several times and reducing lifetime of some of the long-term radioactive waste (transmutation of minor actinides). They thus offer a valuable alternative in case of uranium shortage and regarding waste issues, but how much valuable, given that they also have higher investment costs? As a last step of our research;

we try to assess *a posteriori* the economic value of this research program from a long-term economic rationality point of view.

The purpose of this chapter is thus to shed light on whether, from a strictly economic point of view, it is worth pursuing R&D on SFRs until 2040. To achieve this goal, we developed a model based on the real options theory that compares the consequences of the two possible outcomes: with the SFR option (i.e. with the research option), and without. It is assumed that only two technologies are competing: SFR and LWR (i.e. current technology), and we focus on uranium price issues to determine the relative competitiveness of technologies. If the SFR option has been chosen in 2012, in 2040 decision makers will have to choose whether to invest in SFR or not, depending on the technology's relative competitiveness compared to LWR; if the R&D option is not chosen in 2012, the only choice in 2040 would be to keep operating LWRs. As a result of the comparison carried out in our study, more economic value seems to lie in the R&D option.

The chapter first goes through literature about real option theory in Section 1, then explains the building of the model in Section 2. The applications and results of the model to our case study are presented in Section 3. Section 4 explores a sophistication of the model by including endogenous effects on uranium prices. Section 5 eventually discusses the main results and concludes.

1 Literature review

A literature review shows that the theory of real options has already been applied to such fields as energy and R&D investments. Martinez and al (2013) put forward a review of research works applying real options theory to electricity generation projects. They showed that real options were used in order to assess the project's value in most cases at the planning stage of the project, when investment decisions are made under uncertainty of future prices. Various kinds of prices are at stake in electricity generation projects: electricity prices as in Barria, 2011, Takashima, 2010, Madlener and Stoverink, 2011, Madlener et al, 2005 especially in deregulated market contexts; fuel prices, as in Davis and Owens, 2003, who assess the value of renewable technologies in the face of uncertain fossil fuel prices; or both the price of energy inputs and that of electricity as in Roques et al, 2005 and Bobtcheff, 2006, who focused on the choice between a nuclear or natural gas-based power generation, or as in Kumbaroglu et al, 2006, and Fernandes et al, 2011who focused on the diffusion prospects of renewable technologies.

Beyond the prices for energy goods, uncertainty also resides in costs such as investment costs, especially for capital-intensive technologies: Rothwell, 2006 studied how investment cost conditions for boiling water reactors in the US could lead (or not) to new purchase orders for reactors, and Guillerminet, 2002, investigated how different financing methods and the associated costs could influence the investment decision in nuclear equipment.

CO_2 prices are also submitted to uncertainty due to climate policy evolution: Reedman et al, 2006, model carbon price uncertainty in the Australian context ; Taverdet-Popiolek, 2010, shows that investors in the field of coal power plants should rather wait for information on the carbon market before starting their investments; Liu et al, 2011, model uncertainty CO_2 prices as well as fuel and electricity to assess optimal timing for generation investment; they thus take into account uncertainty not only from the market but also from policy.

Energy and climate policies encouraging investments can thus be evaluated through the uncertainty of incentives, such as in in Lee and Shih, 2010, evaluating the renewable energy policy in Taiwan, or Siddiqui et al, 2007, also assessing a US federal program for R&D on renewables. The book by Ostertag et al, 2004, provides a collection of articles on the real options approach in the energy sector, while taking into account synergies with climate policy.

More sophisticated studies take into account uncertainty on prices and costs at several levels of the project: uncertainty on future sale prices, budget overruns in the project, uncertainty on performance, uncertainty on market targets, uncertainty schedule for the project, as in Huchzermeier and Loch, 2001, Perlitz et al, 2002, Wang and Hwang, 2005, who used such an approach to select a R&D projects or portfolios; or Martinez and Rivas, 2011 who applied it to the Mexican electricity system.

Beyond economic uncertainties on prices and costs, real option theory also allows modeling uncertainty on technology: on renewable technologies that depend on natural phenomena such as wind (Martinez & Mutale, 2012, Martinez & Mutale, 2011) or water for hydropower projects (Kjærland and Larsen, 2009, Kjærland 2007); or new concepts with a risk on innovation such as nuclear, as for nuclear reactors in Cardin et al, 2010, or nuclear waste disposal in Ionescu, 2011, who assesses the value of reversibility related to the geological disposal of radioactive waste packages.

This non-exhaustive literature review which shows the application field of real option values is quite broad and addresses the issue of investment and risk management in industries where innovation strategy is key. Among all these examples from the literature many presents more or less similar questions as the one raised in this paper, about R&D and investments choices, nuclear and electricity fields. It is nevertheless interesting to highlight in particular the research by Epaulard and Gallon, 2001, which used a real options model to assess the relevance of building a European pressurised reactor (EPR) prototype, which would provide an alternative technology in the long term in the case of high gas prices. In terms of guarantees, this approach is similar to ours though it does not concern the Generation IV technology with the sustainability advantages and uncertainties that characterize its cost.

Our research is rather innovative since it covers the issue of a pioneering technology that can only be deployed on the market in the long term. The uncertainty on this date (2040) both in terms of the uranium raw material and the competitiveness of the technology has never, to our knowledge, been studied using the real options theory.

As for the modeling used in real options, we distinguish two main currents: on the one hand, the models coming from environmental economy using decision trees, with fixed windows of opportunity and on the other hand, the models coming finance who models uncertainty as Brownian motion, and have mobile windows of opportunity. In our case, since we consider fixed dates in 2012, and 2040, we logically use a decision tree modeling with fixed windows of opportunity for decision and information gain as in Henry, 1974 [a, b] and Arrow & Fischer, 1974.

This following section details the model and the simplifying assumptions that we have developed to assess the relevance of continuing R&D on fast reactors beyond 2012.

2 Method: model based on real option theory

The present study furthers previous research on using real options theory to estimate the R&D economic value for Generation IV nuclear reactors (see Taverdet-Popiolek and Mathonnière, 2010). This previous work already used a decision tree to show the different options in discrete scenarios with fixed windows of opportunity. However, it focused on the risks inherent to research (reaching safety objectives, operability, reliability and acceptable investment cost). We have taken a different angle this time since the risks related to research are disregarded, whereas uncertainty focuses on the overcost of SFRs compared with LWRs and on the future price of natural uranium with the deployment of nuclear energy worldwide (though it could be hindered too by the Fukushima disaster).

This section describes the model step by step: subsections 2.1 and 2.2 present the options for decision makers in 2012 and 2040 and subsection 2.3 explains the concept of flexibility brought by the real options approach. Subsection 2.4 establishes in mathematical terms the areas of competitiveness for both technologies at stake (LWR and SFR). The way uncertainty is modelled for the two key parameters (uranium price and SFR overcost) lies in subsection 0. Subsection 2.5 sums up the decision process with a decision tree. Subsections 2.6 and 2.7 show the mathematical modelling of the costs of the two options for the decision in 2012 (with or without R&D) and in the end, 2.8 explains how the value of the R&D is assessed from the comparison of these costs.

N.B.: the mathematical modeling for this model was made by Dr. Nathalie Taverdet-Popiolek.

2.1 Decision in 2012

As we said in the introduction, it is known that for the time being, the R&D option has been chosen. We nevertheless explain in this paragraph the two possible outcomes that could have occurred in 2012.

In our modelling, the public authorities are responsible for making a decision that is in the interest of the general public. The decision to be made in 2012 is assumed to be binary: "halt R&D on Generation IV reactors" or "finance R&D in this field".

An overall approach is used to compare the two possible choices in 2012. This involves minimising the discounted sum at this date of all costs associated with nuclear electricity generation (frontend cycle, electricity production, backend cycle) over the 2012 - 2150 period.

2.2 Window of opportunity in 2040

The choice of an electric utility to start building a new reactor technology presupposes that a certain number of stages have already been successfully completed. Since the ASTRID prototype is expected to start operating around 2020 and feedback has to be collected before a first-off reactor can be built around 2030, the year 2040 is often taken as a marker in future scenarios signalling the start of a possible industrialisation of SFRs.

Under these conditions and in the case where the R&D option is chosen in 2012, the decision-maker will be confronted with another decision to make in 2040: "give the go-ahead to start building the fast reactor technology" or "veto its industrial-scale construction" if it proves to be insufficiently competitive compared with the former technology. France would therefore continue to operate LWRs since it is assumed that only these two technologies are competing.

The study is placed within a French context without any technology exchanges outside its borders. Therefore, if no R&D is conducted in 2012, then it is assumed that there will be no Generation IV reactors in 2040. No other window of opportunity is considered in the model and the window of opportunity is fixed as in Henry's value option models (Henry, 1974). This model includes two periods (model with simple real options) contrary to the one that has been used in the past where an additional window of opportunity was foreseen in 2080 (see Taverdet-Popiolek and Mathonnière, 2010, as mentioned earlier).

The first period ranges from 2012 to 2040 while the second ranges from 2040 to 2150.

2.3 Flexibility associated with the decision to conduct research

"*We will know better about tomorrow than we know now about after tomorrow*" wrote Henry, 1974, when he was citing one of the three conditions needed to use the real options theory, with the two others being "*in an uncertain universe*" and being faced with "*choices of variable flexibility*" (see in particular Bancel and Richard, 1995, or Taverdet-Popiolek, 2006).

As previously mentioned, the uncertainty on the price of uranium and the overcost associated with fast reactors as of 2040 actually determines their competitiveness. The higher budget is mainly due to the investment cost associated with fast reactors. The stricter safety standards will impact both technologies (fast and light water reactors) in the same manner.

It is assumed that the information on the competitiveness is revealed in 2040, thus making it possible to choose to launch (or not) the fast reactor technology with full knowledge of the facts. This is why the decision to conduct or cancel R&D (condition assumed to be necessary and sufficient to acquire the fast reactor technology in 2040) in 2012 is considered flexible. The decision to halt R&D is completely irreversible since there will be nothing more in the future (cost of resuming such a programme is prohibitive, loss of knowledge) and only the LWR technology will be available, which means that uranium will still be used, even at a very high price.

The problem is to know whether the cost of flexibility is justified. This cost is the R&D subsidies for the SFR field to make sure that the technology is ready in 2040, regardless of its level of competitiveness.

Before calculating the costs associated with alternative decisions, the competitive area between the LWR and SFR technologies has to be determined.

2.4 Equivalence between LWR and SFR costs: a linear relationship

The following assumptions were used to define this zone of equivalence (Figure 1):

The annual electricity production is stable over the entire period of study. It is denoted by the letter Q. The availability of LWRs and SFRs is supposed to be the same and will therefore have no influence on electricity production Q. There is a possibility that, being a less mature technology, SFRs should have more availability problems at least at the beginning of its exploitation, but this difference of performance can be taken into account in the SFR overcost.

With the uranium price equivalent to €100/ kg, the cost of fuel represents 5% of the total cost of a LWR. We suppose that, even if the price of uranium grows, there will be no notable technological progress in order to reduce the part of uranium in the total cost of LWR. There from we consider that the part of fuel in the total LWR cost is fixed to 5%.

The total cost of the LWR fleet needed to produce the annual quality of electricity Q (with the uranium price at €100/kg) is written "Cost LRW $fleet_{100}$" (shortened to "Cost LWR_{100}"). This total cost takes into account the frontend cycle, backend cycle and electricity production.

If the price of uranium increases by p, then:

$$\text{Cost } LWR_p = \text{Cost } LWR_{100} \times (1+0.05p). \qquad (1)$$

The cost of an SFR does not depend on the uranium price, nor does it depend on the price of plutonium which is assumed to be free of charge in France. This last hypothesis is relevant in this particular context, since plutonium is already generated by the reprocessing of LWR waste, which is a legal obligation in France. Its cost is thus usually considered to be negligible, but in most other contexts, it would be relevant to take a much higher cost into account (for instance in India, as in Suchitra & Ramana, 2011). The overcost of an SFR compared with a LWR is mainly due the higher investment cost. We nonetheless take into account the overcost that it represents over the total cost (investment, production, frontend, backend). In particular the production cost of plutonium is included in this overcost. For this reason, cases of costly plutonium can be taken into account by considering higher SFR overcosts, which is illustrated in the paper by the simulations with the higher SFR reactor overcosts.

Given that s represents the overcost of an SFR in relation to an LWR where uranium is worth €100/kg, then:

$\underline{\textit{Cost SFR} = \textit{Cost LWR}_{100} \; x \; (1+s).}$ (2)

We obtain the equivalence of the two methods of production when:

$\underline{\textit{Cost LWR}_{100} \; x \; (1+s) = \textit{Cost LWR}_{100} \; x \; (1+0.05 \; p).}$ (3)

That is to say when:

$\underline{s = 0.05 \; p}$ (4)

The zone of equivalence is linear: a straight line that cuts the (p x s) graph in half: SFR competitive area and LWR competitive area from 2040.

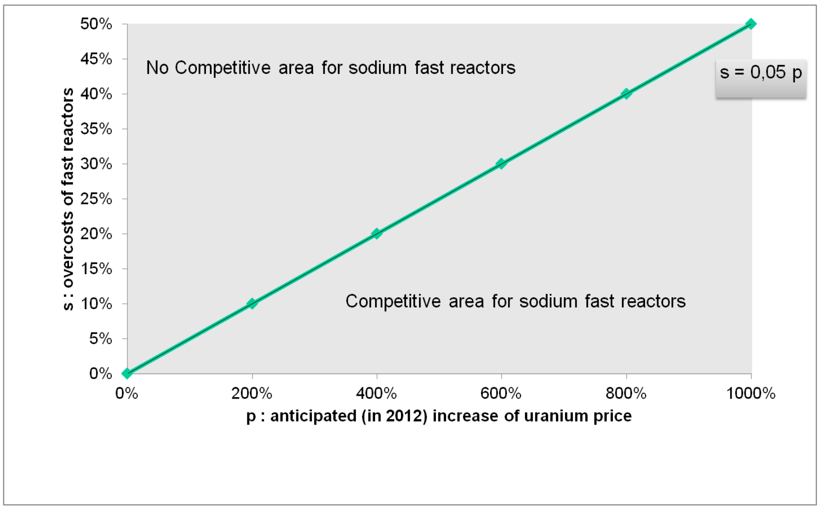

Figure 23: SFR and LWR competitive areas from 2040 and line of equivalence for the two technologies from an economic viewpointUncertainty

As previously mentioned, there is uncertainty both on the price of uranium from 2040 and on the overcost of SFRs.

2.4.1 Price of uranium

The uranium price is estimated at €100/ kg for the first period. It is then assumed from 2040 onwards that it rises by p to remain stable throughout the second period. The rise, p, is expressed as a percentage of the price prior to 2040 and is assumed to follow a Gaussian distribution with a mean p_m and a standard deviation σ_p.

The information is revealed in 2040 (complete gain of information) as shown in Figure 2. It should be pointed out that the assumptions from 2040 on the mean price and on the standard deviation are calculated in 2012 (forecasts made at the time of the decision).

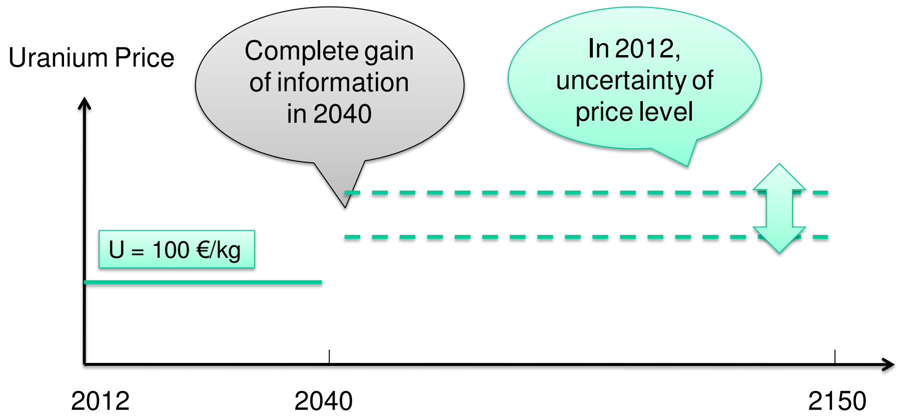

Figure 24: Uranium price rise in 2040

2.4.2 SFR overcost

Over the second period, it is assumed that the SFR overcost, compared with a LWR in the first period, follows a Gaussian distribution with a mean s_m and a standard deviation σ_s.

2.4.3 Implication of introducing uncertainty in the model

As a consequence of introducing uncertainty in the form of Gaussian distributions for the uranium price and SFR overcost, the separation between SFR and LWR competitive areas is not binary anymore. The line of equivalence still represents the zone where SFR and LWR are equally competitive; but there is a non-zero probability that SFR could be competitive in the LWR competitive area, which means that SFR integration could occur in the nuclear fleet, and vice versa.

2.5 Decision tree

In 2012, the public authorities will be faced with a decision tree (see Figure 3) where they will have to choose between continuing research on future reactors or halting this research taking into account the impact of their choice on future costs. Continuing R&D will open a new window of opportunity in 2040 which involves choosing to build (or not) the innovative technology, with the decision being made with full knowledge of the facts, i.e. understanding its level of competitiveness compared with the other technology. The costs are calculated using a decision tree according to a *backward induction* method where the costs are minimised at every step (node) of the decision process (see Bancel and Richard, 1995 and Taverdet-Popiolek, 2006).

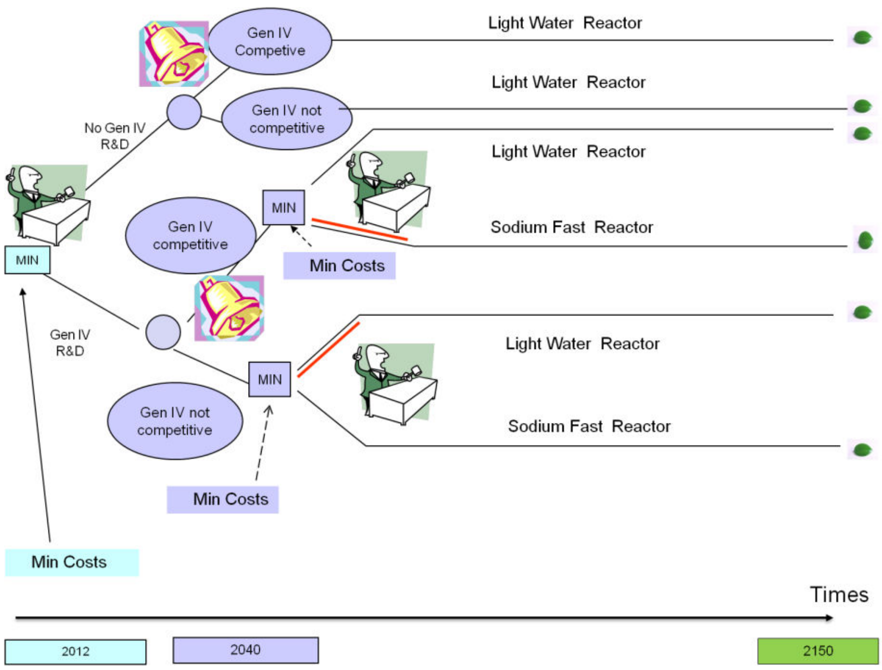

Figure 25: Decision tree

2.6 Discounted cost of the decision to halt R&D

By refusing to conduct R&D in 2012, France will condemn itself to the LWR technology only. The first period is represented by the following interval: [T_0 = 0 ; T_1 = 28] while the second by: [T_1 = 28 ; T_2 = 138].

The discount rate is expressed as a_1 for the first period and as a_2 for the second.

The total discounted cost over the entire duration during which research is not conducted (written Z) is expressed as follows:

$$Z = \overline{COST}\,(LWR) =$$

$$Cost\ LWR_{100}\left[\int_{T_0}^{T_1} e^{-a_1 t}\,dt + \int_{T_1}^{T_2} e^{-a_2 t}\,e^{(a_2-a_1)\times 27}dt \int_{-\infty}^{\infty}(1+0{,}05p)f_p\,(p)dp\right] \quad (5)$$

The limit applied is]-∞ ; + ∞ [for p is a price variation variable and can be negative. Nonetheless the level of p_m and σ_p makes it mainly about positive values, representing a price rise, which concerns mostly our case study.

The expression can be simplified by the following calculation:

$$\int_{-\infty}^{\infty}(1+0{,}05\mathrm{p})\mathrm{f_p}\,(\mathrm{p})\mathrm{dp} = 1 + 0{,}05\ \mathrm{p_m} \quad (6)$$

This makes it possible to obtain a linear expression as a function of p_m. Finally:

$$Z = \overline{COST}(LWR) =$$

$$Cost\ LWR_{100}\left[\int_{T_0}^{T_1} e^{-a_1 t}\,dt + \int_{T_1}^{T_2} e^{-a_2 t}\,e^{(a_2-a_1)\times 27}dt\ (1+0{,}05\ p_m)\right] \quad (7)$$

It should be pointed out that the function $\overline{COST}(LWR)$ is linear in relation to p_m (mean increase in the uranium price). It is independent of the standard deviation: this means that the cost of halting research remains the same regardless of the uncertainty on the uranium price rise.

To convert this total cost into a mean unit of annual cost, it must be divided by the quantity of electricity generated each year Q and discounted, i.e.:

$$Q\,[\int_{T_0}^{T_1} e^{-a_1 t}\,dt + \int_{T_1}^{T_2} e^{-a_2 t}\, e^{(a_2 - a_1)\times 27}\,dt]. \quad (8)$$

The discount coefficient is then denoted as τ .

$$\tau = \int_{T_0}^{T_1} e^{-a_1 t}\,dt + \int_{T_1}^{T_2} e^{-a_2 t}\, e^{(a_2 - a_1)\times 27}\,dt \quad (9)$$

Therefore the mean cost per unit of generated electricity is equal to:

$$\frac{Z}{\tau Q} \quad (10)$$

2.7 Discounted cost of the decision to conduct R&D

The nuclear reactor fleet annually produces a quantity of electricity Q:

by means of the LWR technology prior to 2040,

by means of the SFR technology after 2040 if it proves competitive, or otherwise by the LWR technology. For the diffusion of SFR technology, we have to consider the limits of the fleet's capacity which does not allow for the immediate switch to the new technology (life time of LWR plants already in service, plutonium availability, etc.).

The cost of R&D over the period [$T_0 = 0$; $T_1 = 28$] must be taken into account.

The letter A denotes this discounted cost:

$$\boldsymbol{A = \int_{T_0}^{T_1} e^{-a_1 t}\, Cost\ R\&D(t)\,dt} \quad (11)$$

The letter B represents the production cost during the first period (only for the LWR technology).

$$\boldsymbol{B = Cost\ LWR_{100} \int_{T_0}^{T_1} e^{-a_2 t}\,dt} \quad (12)$$

The production cost is calculated for the second period based on the fact the electricity will be generated by LWRs in the SFR non-competitive area and generated by SFRs in the competitive area. The assumption that SFRs are progressively integrated into the fleet must also be taken into account.

Let C be the discounted cost of production during the second period in the case where R&D has been launched in 2012:

$$C = e^{(a_2-a_1)\times 27} Cost\ LWR_{100} \left[P \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\frac{s}{0,05}} (1+0,05p) f_p(p)dp + \int_{\frac{s}{0,05}}^{\infty} (1+s) f_p(p)dp \right] f_s(s)ds + P' \int_{-\infty}^{\infty} (1+0,05p) f_p(p)dp \right] \quad (13)$$

with the parameters P and P' expressing both the discounting and the progressive integration of SFRs. They are described in § 3.1.2.

Here again, the limit taken into account for s is]-∞ ; + ∞ [for s is a cost variation between the SFR cost and the LWR cost and can theoretically be negative. Since we consider an overcost, i.e. a positive variation, the level of s_m makes it mainly about positive values.

Finally, the cost of the decision to conduct R&D in 2012 amounts to the sum of the three expressions, A, B and C:

$$\boldsymbol{\overline{COST}(SFR\ R\&D) = A + B + C} \quad (14)$$

The mean cost per unit of generated electricity is:

$$\frac{\mathrm{A+B+C}}{\tau \mathrm{Q}} \quad (15)$$

2.8 Comparing the option value with the R&D amount

The two discounted costs need to be compared and the R&D amount needs to be defined for which both decisions “conduct R&D” or “halt R&D” are considered to be equivalent.

It is worth calculating the cost of the decision to conduct R&D without integrating the actual expense of R&D. Therefore, the difference between the cost to halt R&D and the cost to conduct R&D (positive difference owing to the flexibility associated with the decision to conduct R&D) represents the limit not to be exceeded in terms of the R&D budget allocated to Generation IV fast reactors, i.e.:

$$Z - (B+C) \tag{16}$$

Strictly speaking, the value of the electricity produced by the prototype should be integrated into the R&D costs. We have not taken this aspect into account in order to simplify the model, which penalises the decision to conduct R&D.

3 Results and simulations

This section describes the results of numerical applications and simulations performed using the model.

Firstly, the assumptions defining all the parameters of the model are detailed, i.e. : i) nuclear electricity production Q which is assumed to be stable, ii) annual cost of the LWR fleet (Cost LWR $fleet_{100}$), iii) discount rate for the first and second period, iv) proportion of SFRs in the fleet and its progress over time, v) means and standard deviations of probability density functions, vi) overcost of SFRs, and vii) uranium price rise.

The numerical applications provide an assessment of the costs for each decision, as well as an estimate of the limit not to be exceeded for the R&D budget allocated to Generation IV reactors. The simulations are used to calculate these same costs by varying the parameters of the model (mean of the overcost and of the uranium price rise, uncertainty, discount rate, etc.) so as to visualise different decision-making contexts.

3.1 Assumptions of the model parameters

3.1.1 Nuclear electricity production and discounting

Our study was based on the total annual costs for an entire fleet producing a quantity Q = 430 TWh of electricity. The total annual cost of the LWR fleet is: Cost LWR $fleet_{100}$ = €20 G

The discount rate applied is the public rate: a_1 = 4% before 2040 and a_2 = 2% after 2040.

3.1.2 SFR integration

The progressive integration of SFRs into the fleet from 2040 is taken into account on the basis of past LWR constructions, their life spans and the available plutonium resources (for SFRs). Four periods are taken into consideration as shown in Figure 4.

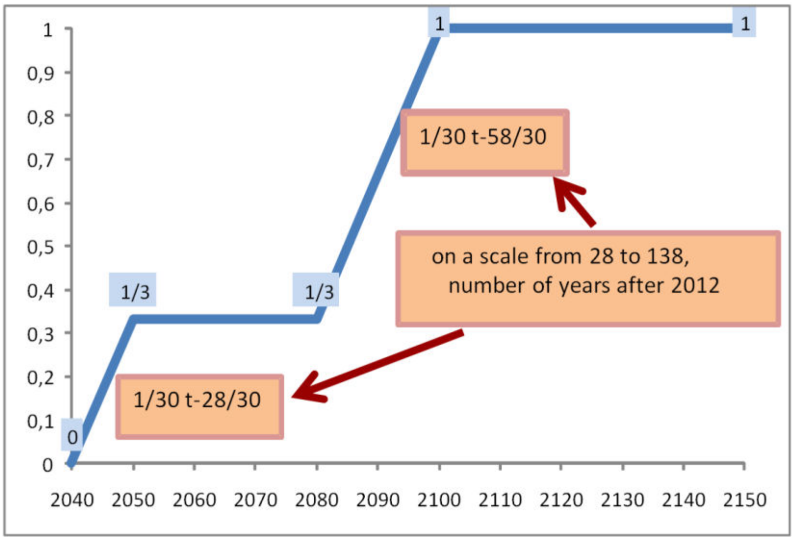

Figure 26: SFR integration assumptions

The following expressions, P and P', take into account SFR integration assumptions and discounting:

$$P = \int_{T1}^{T_1^{'}} \left(\frac{1}{30}t-\frac{28}{30}\right) e^{-0,02t}dt + \int_{T_1^{'}}^{T_1^{''}} \frac{1}{3} e^{-0,02t}\, dt + \int_{T_1^{''}}^{T_1^{'''}} \left(\frac{1}{30}t-\frac{58}{30}\right) e^{-0,02t}dt + \int_{T_1^{'''}}^{T2} e^{-0,02t}\, dt \quad (17)$$

$$\boldsymbol{P' = \int_{T_1}^{T_2} e^{-0,02t}\, dt - P} \quad (18)$$

With $T_1 = 28$, $T'_1 = T_1+10 = 38$, $T''_1 = T'_1+30 = 68$, $T'''_1 = T''_1+20 = 88$, $T_2 = 138$.

3.1.3 Reference assumptions for the probability density functions

The uranium price rise, p, is given as a percentage of the price during the first period and is assumed to follow a Gaussian distribution with a mean p_m = 240% and a standard deviation σ_p of 100%. Over the period [$T_1 = 0$; $T_2 = 138$], the SFR overcost, s, follows a Gaussian distribution with a mean s_m = 12% and standard deviation σ_s equival to 1/30, i.e. 3.33%.

This combination of mean values for the distributions s and p was chosen as follows:

The mean of the s distribution is based on an expert analysis in which the SFR overcost is estimated in relation to the LWRs in service in the first period. The investment item generates the overcost, with the other items remaining almost the same. Assuming that uranium costs €100/ kg and in light of this overcost, the assessment of the overall overcost (investment, operation, cycle) amounts to 12%.

Once s_m has been calculated, p_m (mean of the p distribution) is chosen so that the (p_m, s_m) combination is located on the line of equivalence for both technologies $s_m = 0.05\ p_m$, which leads to a p_m of 240%.

The standard deviations were chosen to include an appreciable level of uncertainty while limiting scatter around the mean.

3.2 Results on reference case

The numerical applications were performed with the Maxima software.

$\underline{\overline{COST}(LWR) = \mathrm{Z} = 668{,}4\ \mathrm{G€}}$ *cf. (7)*

An annual cost of $\frac{\mathrm{Z}}{\tau \mathrm{Q}}$ = €49.12 per MWh with $\tau = 31{,}64$ was deduced. *cf. (10)*

$\overline{CO\hat{U}T}(\ SFR\ R\&D\ decision) = \mathrm{B} + \mathrm{C} =\ 664{,}9\ \mathrm{G€}$

An annual cost of €48.87 per MWh was deduced.

Considering the model's simplifying assumptions, with a mean uranium price rise predicated at 240% and an mean overcost of 12% for SFRs compared with LWRs (with moderate uncertainty on these two random variables), the public authorities will be able to spend up to €3.5 G for research on future reactors. cf. (16)

It is worth varying the model's parameters to observe the variation in the amount that the public authorities are willing to spend on R&D and create a mapping of these variations. As we said in the introduction, the purpose of the study is to illustrate different scenarios of uranium price evolution and SFR overcost, rather than building forecasts based on these parameters.

3.3 Results of simulations

3.3.1 Probability of SFR integration in the nuclear fleet

As mentioned in 2.5, uncertainty introduces non-zero probability of having competitive SFRs in the LWR competitive area and vice versa. Before calculating the research amount available in different decision contexts, the study of such probabilities can give a first assessment of SFR or LWR potential.

These probabilities depend on both SFR overcost and uranium price means and can be calculated for any (p_m, s_m) combination according to the following formula:

Probability of not having competitive SFRs = $\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}} f_p\,(p)dp\right] f_s(s)ds$ (19)

Probability of having competitive SFRs = $\int_{-\infty}^{\infty}\left[\int_{\frac{s}{0,05}}^{\infty} f_p\,(p)dp\right] f_s(s)ds$ (20)

The sum of the two terms is of course 1.

The figure below shows the results of the calculation of the probability to have competitive SFRs in the case of different (p_m, s_m) combinations, the standard deviations being the same as in the reference case (σ_p = 100%, σ_s = 3.33%). The probability to have competitive LWRs can be easily deduced.

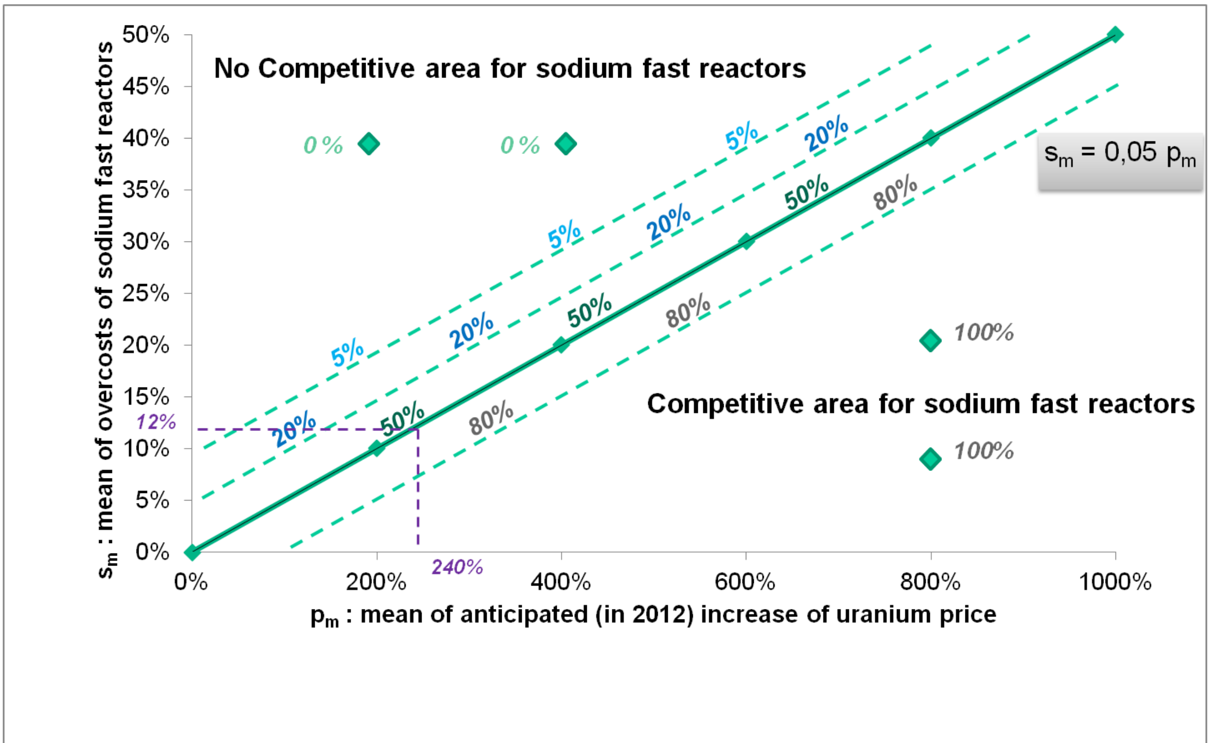

Figure 27: Probability of introducing SFRs in the nuclear fleet for different (pm, sm) combinations

The probability on the equivalence line is 50%. One striking results is that on each line parallel to this equivalence line the probability remains the same. (p_m, s_m) combinations that are located very far from the equivalence line on the (p_m x s_m) graph reach extreme values (100% or 0%). Far enough from the equivalence line, the uncertainty tends to disappear.

3.3.2 Cartography of option values for different combinations (mean uranium price rise p_m and mean SFR overcost s_m)

Simulations were performed with (p_m, s_m) combinations that differed from the reference combination but with the same standard deviations (σ_p,σ_s). These simulations allow us to observe the maximum amount (A) that would be allocated to R&D according to different positions on the graph (p_m x s_m):

- on the LWR-SFR line of equivalence,
- in the LWR competitive area,
- in the SFR competitive area.

Figure 5 shows the results of these simulations: the maximum amount (A) (in €G) is indicated for each combination.

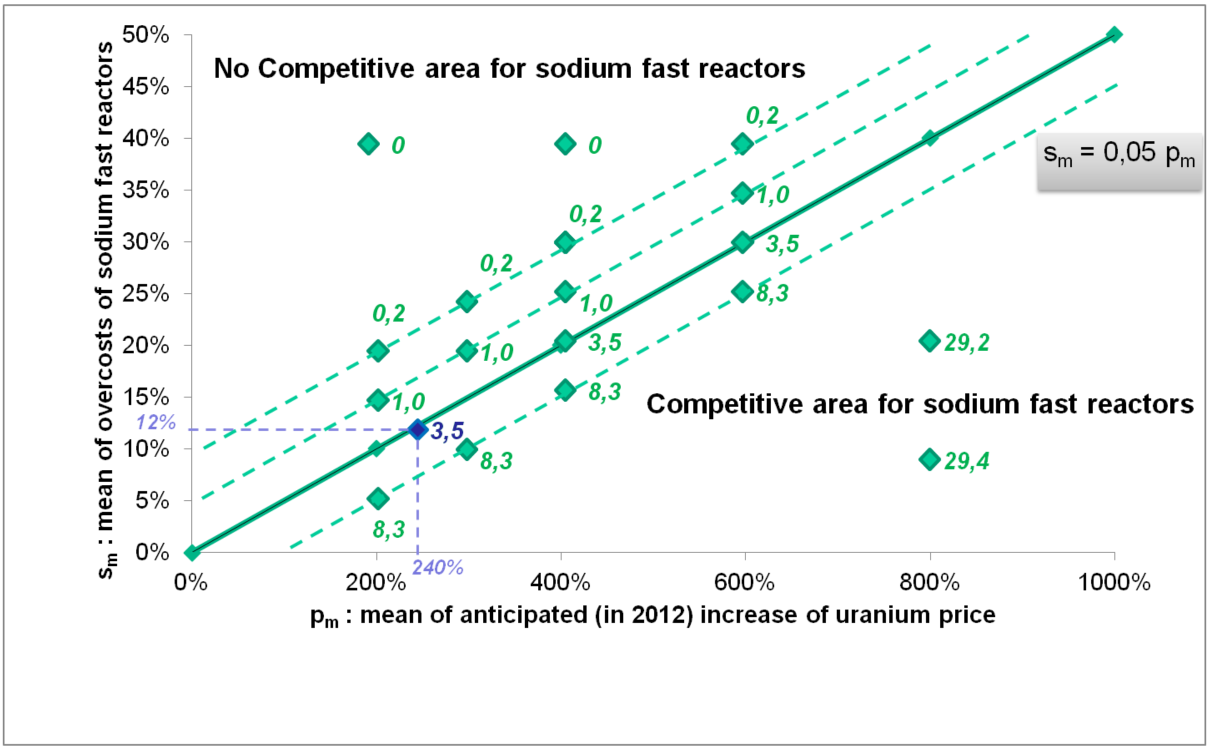

Figure 28: Simulation results: cartography of values of (A) in €G

The results show that the amount (A) allocated to R&D becomes non-zero on the line of equivalence which is even the case when moving away from this line into the SFR non-competitive area. As expected, this amount nevertheless grows increasingly smaller when moving away from the line of equivalence in the SFR non-competitive area and increasingly higher when going in the other direction.

It is also worth pointing out that practically the same amount (A) allocated to R&D is found for the (p_m, s_m) combinations located on the line of equivalence. By extrapolating this observation, it can be seen that the same amount (A) is allocated to research for each line parallel to the line of equivalence for all combinations belonging to this line, like it was observed in 3.3.1 in the calculation of probabilities of having competitive SFRs. At the same level of uncertainty in absolute, the amount allocated to R&D is determined by the relationship between p_m and s_m.

3.3.3 Expected gain due to overcost reduction

The amount (A) allocated to R&D is found by calculating the difference between the cost to halt R&D and the cost to conduct R&D (cf 2.9, (16)), which is to say the difference between the total cost of running a LWR fleet without the possibility of using SFR option and the total cost of a nuclear fleet where SFR are built if competitive. It may thus be seen simply as the cost gain offered by the choice of keeping the SFR option open over the choice of a LWR-only fleet, this gain being then available to finance R&D.

The results of the simulations presented in Figure 6 (cf 3.3.2) allow us to observe how this cost gain (A) may vary depending on the SFR technology overcost mean s_m. The graph below, in Figure 7, shows the variation of this cost gain in the reference case for the rise of uranium price (p_m = 240%) and with the overcost mean s_m varying between 2% and 40%.

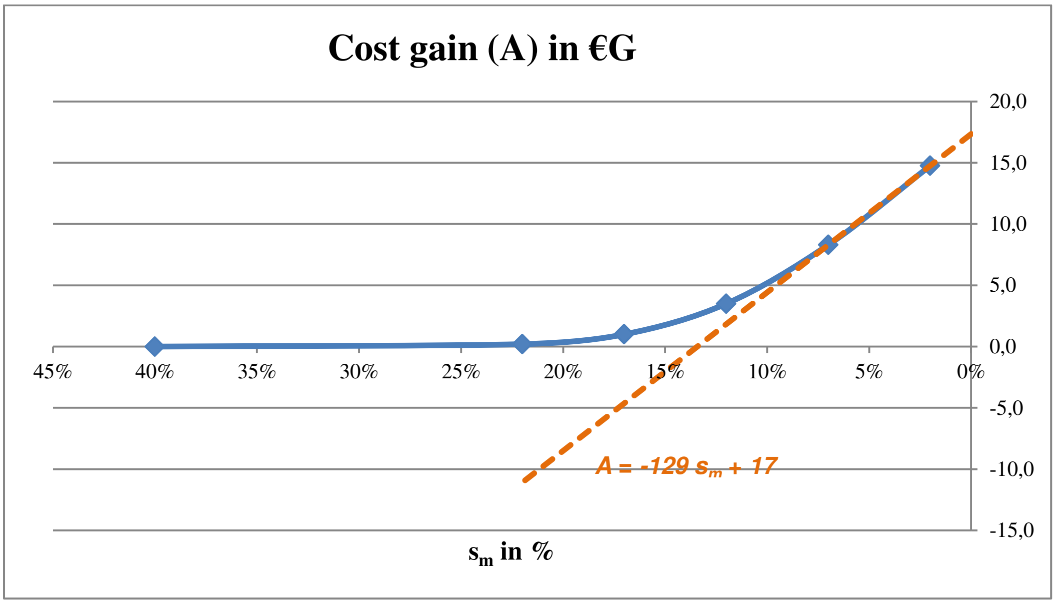

Figure 29: Variation of gain cost (A) depending on overcost mean sm (pm = 240%)

The curve shows that for SFR overcost means s_m above 20%, there will be no cost gain. On the other hand, for SFR overcost means below 20%, the more the SFR overcost gets reduced, the more the cost gain is high. For instance, reducing the overcost from 12% to 7% increases this cost gain by €4.8 G (from € 3.5 G to € 8.3 G), whereas reducing the overcost from 7% to 2% increases this cost gain by € 6.5 G (from € 8.3 G to € 14.8 G).

A linear zone is identified on the curve for the overcost mean values below 10%: in this zone, the slope is approximately 130 which means reducing the overcost mean by a 1% step increases the cost gain by € 1.3 G.

Another way of interpreting these results consists in assessing how much can be invested to reduce the SFR overcost without losing the cost gain of choosing to keep the SFR option open. Under the hypothesis that the whole amount (A) is dedicated to reduce the overcost and that there is no major technological obstacle preventing from reducing the overcost below a given threshold, the curve shows that there is an interest in investing in such a research for overcost means below 20%.

However these simplified hypotheses should be balanced with two considerations: first, it is not very likely that the whole R&D budget (A) would be dedicated only to cost reduction given the many subjects R&D in SFRs has to deal with; second, there is still a risk that a technological obstacle could prevent the SFR overcost reduction from succeeding. It is a limit of our model.

3.3.4 Influence of the discount rate

A public rate was chosen for the discount rate during the first and second period in the model, i.e. 4% before 2040 and 2% thereafter. This section takes into account two different scenarios:

- a scenario with higher discount rates in case the decider is a private investor: a_1 = 8% for the first period and a_2 = 3% for the second period,
- a scenario with lower discount rates to represent an extreme case where the preference for the present day is very low: a_1 = 1% for the first period and a_2 = 1% for the second one.

These scenarios concern the reference combination (240%, 12%).

Discount rate for 1st period; 2nd period	(A) for the (240%, 12%) combination (in €G)
8% ; 3%	1.23
4% ; 2%	3.49
1% ; 1%	10.76

Table LII: Influence of discount rates (reference combination)

It can be seen that the application of the higher discount rates results in a lower R&D maximum amount, whereas the extremely low discount rates lead to a much higher R&D maximum amount. As

R&D investment bears its fruit in the long term, it is logical that a high discount rate – with preference to the present day – reduces the relevance of such an investment.

3.3.5 Influence of the electricity production

The electricity production (Q) has a direct impact on the cost of the nuclear fleet: Cost LWR_{100} represents a total production cost and is determined so as to follow the same variations as (Q). Modelling of the total fleet cost therefore does not take into account the effect of any economies of scale in the case of increased production and thus increased fleet size. Nor does it take into account any possible impact that an increased fleet size may have on the integration of SFRs: the parameters P and P' are therefore assumed to remain unchanged. If the electricity production (Q) doubles, the Cost LWR_{100} also doubles and consequently so does the maximum amount (A) allocated to R&D since it is proportional to the Cost LWR_{100}.

When Q = 430 x 2 = 860 TWh, then A = 7.0 G€

Similarly, if the electricity production (Q) diminishes, so does the maximum amount (A) allocated to R&D. Given the French government's objective to reduce the share of nuclear in national electricity generation, such a diminution of electricity production (Q) from nuclear power plants could occur: the amount (A) should then proportionally decrease.

3.3.6 Influence of the fuel cost on the overall fleet cost

Based on the model assumptions, the fraction of the fuel cost in the total LWR fleet cost is set at 5%. The highest fraction for the fuel cost found in literature was equivalent to 7%. This explains why the maximum amount (A) is calculated on the basis of a fuel cost of 7% instead of 5%[27].

$$\overline{COST}(LWR) = \mathrm{Z} = 668{,}4\ \mathrm{G€} \quad (7)$$

An annual cost of $\frac{\mathrm{Z}}{\tau \mathrm{Q}}$ = €49.12 per MWh with $\tau = 31{,}64$ was deduced. (10)

[27] Based on the assumption of a fuel cost equal to 7% instead of 5%, a line of equivalence between LWRs and SFRs of the equation:

s = 0.07 p

With an overcost estimated at 12%, the reference combination on the line of equivalence becomes the (171%,12%) combination.

$$\overline{COST}(SFR\ R\&D\ decision) = \text{B} + \text{C} = \ 663{,}9\ \text{G€ (without}\ R\&D\ cost)$$

instead of €664.90 G in the reference case.

An annual cost of €48.87 per MWh was deduced.

The difference between the two costs, i.e. €4.5 G (16), gives the maximum amount (A) that the authorities would rationally spend on SFR R&D. This amount is higher than that obtained for the reference case assuming the cost of fuel to represent 5% of the overall cost of the fleet. This result is consistent insofar as a higher fuel cost (with a mean overcost s_m fixed at 12%) would render LWRs more sensitive to a uranium price increase, which would thus make SFRs more economically interesting.

4 Sophistication of the model: endogenous uranium price

Strictly speaking, the progress of SFRs will have an impact on the risk of the natural uranium price: it should lessen the pressure on the price of this natural resource if the SFR technology catches on. Therefore, it is logical to assume that the mean of the Gaussian distribution p_m should decrease.

Since our study only considers the French fleet, which should have little influence on the international uranium market, such an assumption is acceptable.

Nonetheless, if SFR integration occurs in the French fleet in 2040, it would be likely to spread out in other nuclear countries within the following decades, causing a more significant effect on uranium price.

The total acquisition of information in 2040 on the uranium price for the entire second period is also an extremely simplifying assumption.

To take this effect into account we propose a sophistication of the model. In the case of SFR integration in the fleet, a price drop would occur in 2080, starting a third period in the uranium price timeline.

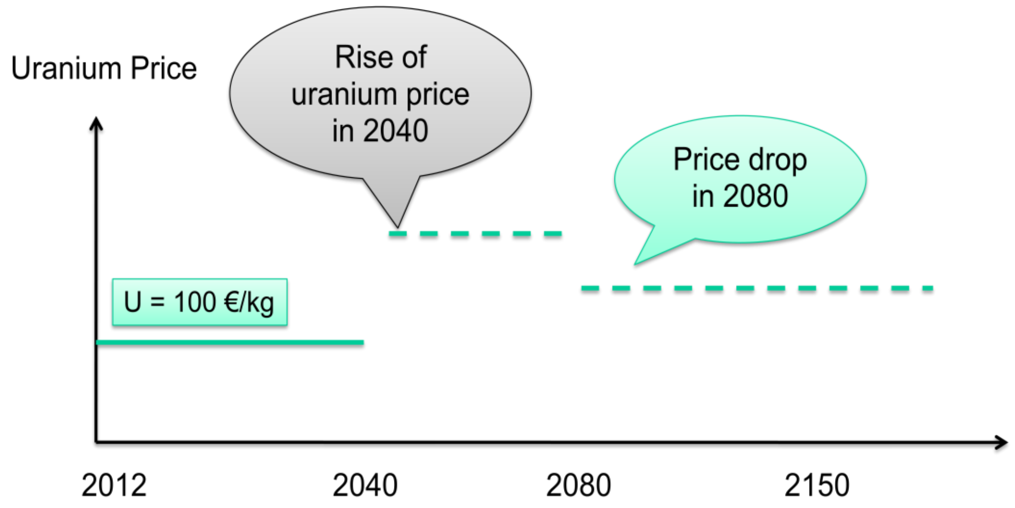

Figure 30: Price drop in 2080 in case of SFR integration

Instead of having two period from 2012 to 2040: [T_0 = 0 ; T_1 = 28] and from 2040 to 2150: [T_1 = 28 ; T_2 = 138], there are now three periods :

- the first is still the same [T_0 = 0 ; T_1 = 28],
- the second one is from 2040 to 2080: [T_1 = 28 ; T_1''= 68],
- and the third one from 2080 to 2150: [T_1''= 68; T_2 = 138], where the price drop can possibly occur.

In the calculation of the option value of research for SFRs, changes are made on term C, which is the discounted cost of production during the second period in the case where R&D has been launched in 2012. In the endogenous model, the calculation remains the same for the second period [2040; 2080], but introduces a probability of a price drop in the third period [2080; 2150]. The cost for this third period is thus composed of the sum of two terms of cost:

- one using the same uranium price mean p_m as in the previous period, multiplied by the probability of not having competitive SFRs : this term represents the case in which SFRs were not competitive during the second period, and did not develop, having not influence in the predicted evolution of uranium price;
- the other using a lower uranium price mean p_m' multiplied by the probability of having competitive SFRs : this term represents the case in which SFRs were competitive during the second period, were integrated in the nuclear fleet and provoked a drop in uranium price.

Detailed calculation is given in Annex D.

For a simple modelling, we suppose that the uranium price mean p_m' of the third period is as a percentage of the price mean p_m of the second period: $p_m' = x\% \, p_m$.

Two hypotheses have been made for the value of p_m' the uranium price mean in case of price drop:

- a low hypothesis considering a modest price drop of 10%, i.e. $p_m' = 90\% \, p_m$.
- a higher hypothesis considering a price drop of 30% i.e. $p_m' = 70\% \, p_m$. Such a hypothesis corresponds to the case when SFR integration in France is the reflection of a larger SFR integration in the international fleet.

The following figures show simulations on a few (p_m, s_m) combinations in both high and low hypothesis.

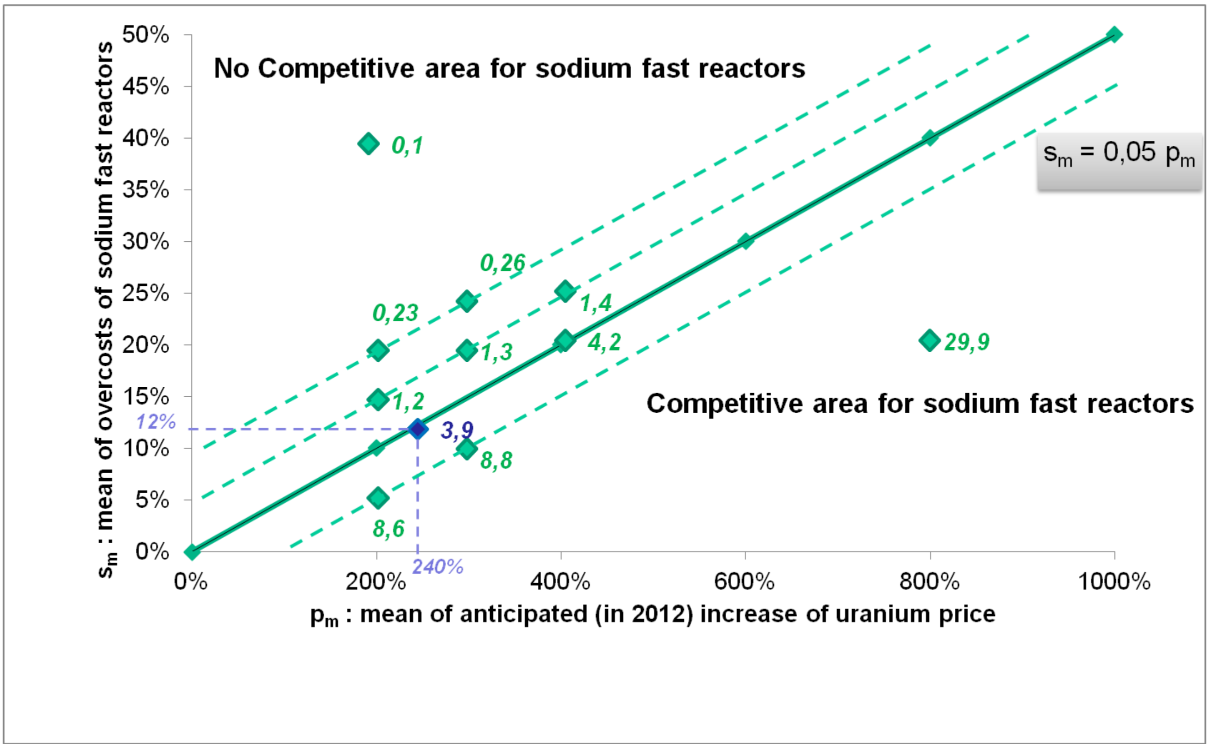

Figure 31: Simulations with endogenous uranium price – 10% price drop in third period i.e. pm' = 90% pm

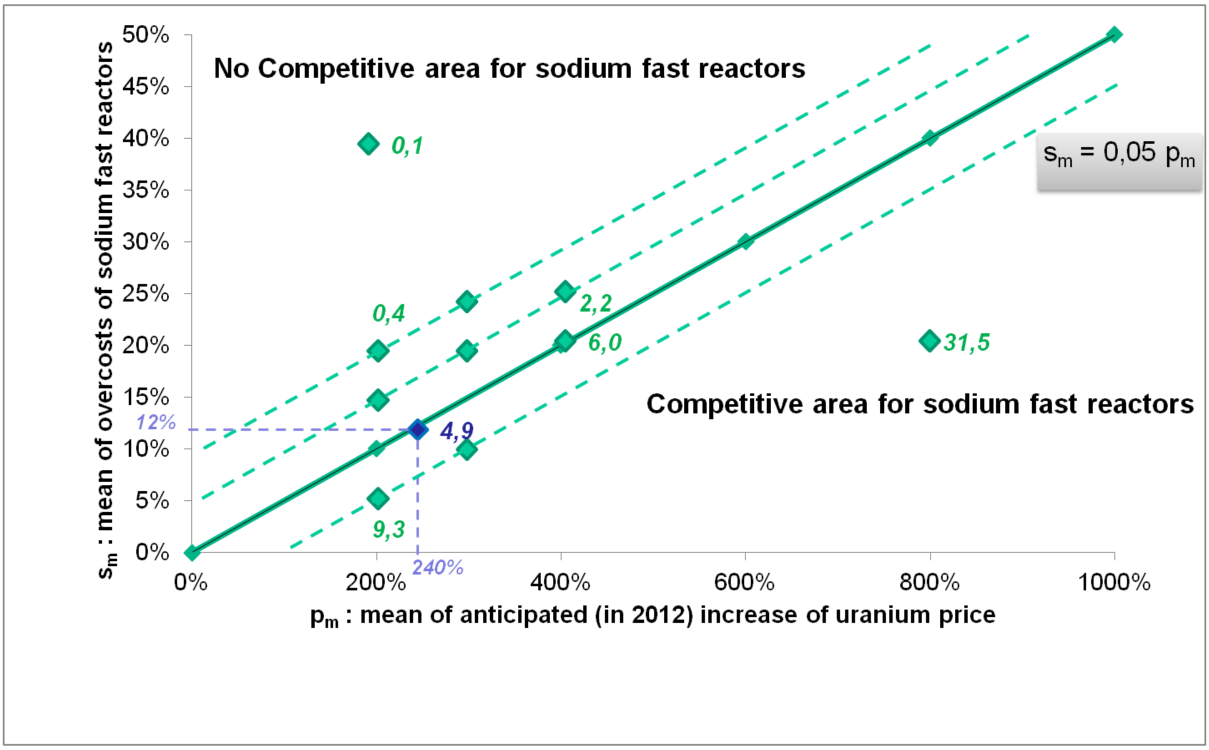

Figure 32: Simulations with endogenous uranium price – 30% price drop in third period

The simulations show that a drop of uranium price due to SFR development increases the amount A available for research and development. Such a result is quite logical since the drop of uranium price in the third period reduces the cost of the SFR and LWR fleet. The comparison between Figure 9 and Figure 10 stresses the fact that the more the price drop is important, the more the amount A increases.

As a result of this endogenous model, not only does the R&D on Generation IV offer a competitive alternative in case of a severe rise of the uranium price, it also improves the competitiveness of LWRs through the feedback effect of SFR development on the uranium market and thus the competitiveness of the whole nuclear sector.

5 Discussion and conclusion

The option value model revealed the following results:

Faced with uncertainty on the future price of uranium and the SFR overcost, the option value associated with the decision to conduct research is non-zero, even in the area where there is a significant risk that SFR reactor is not competitive. Uncertainty and increasing information over time generate the option value.

This is also equal to the maximum budget that the authorities are willing to invest in R&D. It is estimated at €3.5 G based on the reference assumptions for the model which assesses the mean overcost of SFRs at 12% compared with LWRs, and taking into account the case where the probability of SFR reactor being competitive is equal to the probability of LWR reactor being competitive (50%) (which corresponds to a mean uranium price increase of 240%).

With all other assumptions being equal, if the mean overcost of SFRs is increased by a 5% increment i.e. 17% instead of 12% (meaning they are not competitive), the maximum budget allocated to R&D is reduced to €1 G. If the mean overcost of SFRs is lowered by a 5% increment (meaning they are considered competitive in relation to LWRs), this maximum budget for R&D amounts to €8.3 G.

In the same way, all else being equal, if the mean uranium price increase is a 100% increment higher (SFRs are competitive), the maximum budget for R&D amounts to €8.3 G. If the mean uranium price increase is a 100% increment lower (SFRs are not competitive), this maximum budget for R&D amounts to €1 G.

Furthermore, we have highlighted a connection between the amount spent on R&D and the risk associated with the competitiveness of SFRs. The overcost of SFRs should be all the more small since the R&D devoted to this technology (cost viewpoint only) will have been significant. The relationship between the overcost of SFRs and the available R&D amount has been studied in 3.3.4 in order to determine if achieving a reduction of the overcost could retrospectively allow to spend a higher amount for the R&D budget. The relationship shows a linear zone for overcosts below 10%: with a mean uranium price increase of 240%, a 1% step reduction of the overcost in this zone corresponds to a € 1.3 G cost gain for the R&D budget, multiplied by a probability π of success in overcost reduction. We must nonetheless also consider the case (low probability) where research reveals a series of technical deadlocks making it very unlikely to reduce the cost significantly.

Depending on the profile of the decider and his more or less pronounced preference for the present day (which is conveyed through the discount rate), the relevance of R&D proves to be more or less marked. With all assumptions being equal, the discount rates during the first and second period equivalent to 8% and 3% instead of 4% and 2% correspond to a higher preference for the present day and result in a maximum R&D budget of €1.2 G instead of €3.5 G. However, the discount rates of 1% during the first and second period result in an R&D amount equal to €10.8 G, which is considerably higher than that for the reference case.

In order to take into account the feedback of SFR integration on the uranium market, a sophistication of the model has been elaborated taking into account a possible drop of uranium price after a period of SFR development ("state maker" decider, see S. Ramani & A. Richard, 1993. Simulations show that introducing the possibility of a drop in the uranium price increases the budget available for R&D on Generation IV reactors. As a matter of fact, it is logical since the hypothesis of a possible uranium price drop makes the discounted cost of the LWR and SFR decrease, while the cost of the LWR fleet without R&D does not change: the maximum budget for R&D, which is the difference between these two costs, thus increases. In the reference case, the maximum budget available for R&D rises from €3.5 to € 4 G when the uranium price mean p_m drops by 10%, and rise again to € 5G when the uranium price mean drops by 30 %. The remarkable conclusion we can draw from this endogenous model is that choosing to lead R&D on SFRs will also be beneficial for the competitiveness of LWRs.

No matter how informative, it nevertheless remains that these first results have been produced by a simplified economic model that will need to be further developed in order to continue our research.

The main limits of the model are that it is assumed that R&D will necessarily lead to the development of the SFR technology and that there will be no problem with public acceptance of this technology. The first assumption can be loosened by weighing the amount dedicated to R&D by a probability function reflecting the success of R&D. The second assumption being particularly debatable in the wake of the Fukushima disaster, additional uncertainty can be introduced into the model by including a random variable on the public acceptance of the technology. But considering their advantages in terms of waste toxicity, will SFRs have a better chance of being accepted? The cost of safety will rise significantly. This will also have an impact on both LWRs and SFRs, which is why it has no impact on our results.

Moreover, the valuation of the electricity produced by the prototype should be integrated into the R&D costs.

It is also assumed that the part of uranium in the LWR total cost will not change (5%).

Lastly, restricting our study to France is, of course, only an approximation of the reality since technology exchanges between countries should be taken into account. The case of a free rider who profits from the effects of R&D without contributing to its funding should be taken into consideration. However, it is very unlikely that France behave as a free rider in light of its behaviour in the past. Otherwise, France could receive royalties from the sale of its innovation overseas, which has not been integrated into the model.

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7 Annex A: Simulations

These annexes consist in various simulations studying the influence of standard deviations: proportional to the mean, relative influence of σ_p and σ_s, results with very small standard deviations. Detailed calculation of the maximum budget for R&D in the endogenous model is also presented in these annexes.

7.1 Simulations with standard deviations proportional to the mean

In 3.3.2 simulations were performed to assess the amount (A) allocated to R&D with different (p_m, s_m) combinations but with the same standard deviations (σ_p,σ_s) :

- σ_p = 1 = 100%
- σ_s = 1/30 = 10/3% ≈ 3.33%

This was the case for all simulations, representing the same absolute uncertainty for all combinations. It may be worth considering the same combinations with a *relative* uncertainty, i.e. varying the standard deviation in proportion to the mean. In order to vary the standard deviations based on the reference values established by the previous simulations: σ_p = 100% and σ_s = 10/3%, we assigned these reference values to the (400%, 20%) combination which is rather centralised on the (p_m x s_m) graph.

p_m mean uranium price rise	σ_p standard deviation of the p distribution	s_m mean SFR overcost	σ_p standard deviation of the s distribution
200%	50%	10%	10/6%
240%	60%	12%	2%
400%	**100%**	**20%**	**10/3%**
600%	150%	30%	5%
800%	200%	40%	20/3%

Table LIII: Standard deviations varied in proportion to the mean

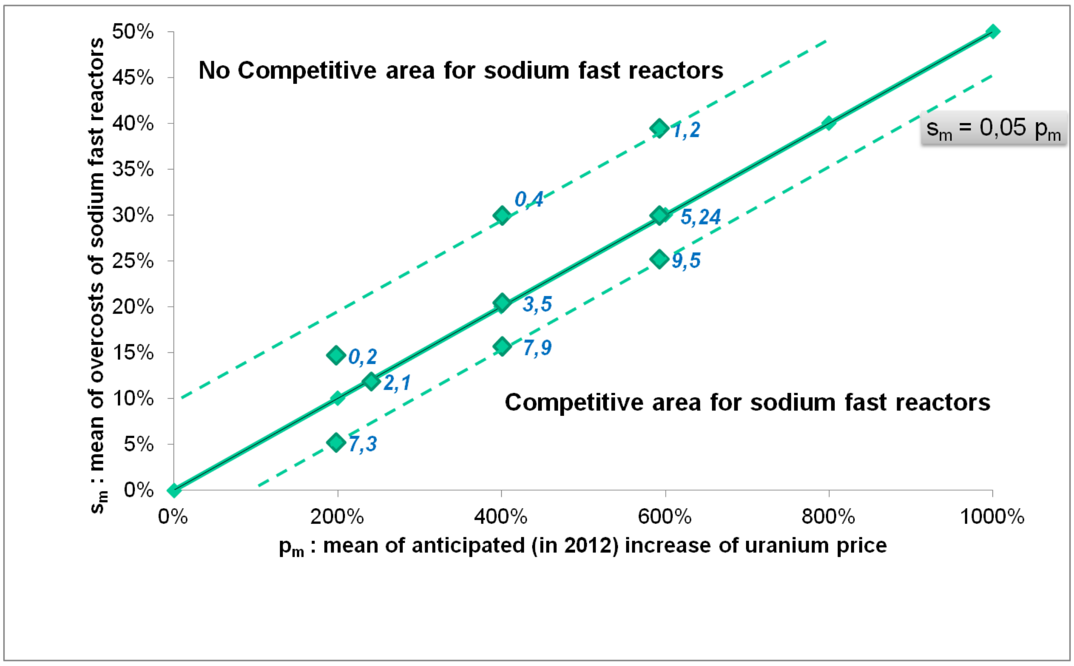

Figure 33: Simulation results with proportional standard deviations ((A) given in €G)

According to these simulations, the amount (A) follows the variations assigned to the standard deviations: the amount (A) is smaller when the standard deviation is lower compared with the reference case and vice versa. The amount (A) is no longer constant along the line of equivalence and the parallel lines, but instead increases with the x-axis and y-axis. The higher the uncertainty, the higher the amount (A). This means that the uncertainty generates the option value.

7.2 Influence of standard deviations σ_s and σ_p

In order to refine the results obtained with the standard deviations varying proportionally with the means, another set of simulations were performed by varying the standard deviations for the reference combination (240%, 12%) so as to detect the sensitivity of the maximum amount (A) to the standard deviation for any given combination. The table below shows the results obtained by varying

σ_p (uncertainty on the uranium price rise) with σ_s (uncertainty on the SFR overcost) remaining constant on the one hand, and by varying σ_s with σ_p remaining constant on the other hand.

σ_p standard deviation of the p distribution (uranium price rise)	Maximum amount (A) for R&D (€G)
5%	0.12
10%	2.10
50%	2.42
100%	**3.49**
200%	6.13
500%	14.68

σ_p standard deviation of the s distribution (SFR overcost)	Maximum amount (A) for R&D (€G)
1/12%	2.91
1/6%	2.91
10/6 %	3.07
10/3 %	**3.49**
10/15 %	4.85
100/6%	10.23

Table LIV: Influence of standard deviations on the amount (A) (reference combination)

The amount (A) for the reference case (240%, 12%) follows the variations of the standard deviation: (A) rises when the standard deviation rises and (A) drops when the standard deviation drops. Again, it is the uncertainty that creates the R&D value with a mean fixed for the uranium price rise and the SFR overcost.

7.3 Results with low uncertainty

Simulations were performed with standard deviations close to zero to observe the effect of low uncertainty not only on the reference case, but also on other possible cases (equivalence between LWR and SFR, SFR competitiveness, SFR non-competitiveness).

On the line of equivalence for the old and new technology as well as in the SFR non-competitive area, the budget allocated to R&D reduces drastically when uncertainty tends towards zero. In the

SFR competitive area, this budget also decreases when uncertainty tends towards zero but remains in the range of several dozen €G.

8 Annex B: Detailed calculation for endogenous model

This annex gives the details of the calculation of the term C in the research option value in the endogenous model.

As said in 4., instead of having two periods from 2012 to 2040: [T_0 = 0 ; T_1 = 28] and from 2040 to 2150: [T_1 = 28 ; T_2 = 138], there are now three periods :

- the first is still the same [T_0 = 0 ; T_1 = 28],
- the second one is from 2040 to 2080: [T_1 = 28 ; T_1''= 68],
- and the third one from 2080 to 2150: [T_1''= 68; T_2 = 138], where the price drop can possibly occur.

In the reference model formula, the terms P and P' take into account SFR integration assumptions and discounting during the second period from 2040 to 2150 [T_1 = 28; T_2 = 138]. In the endogenous model the proportion of SFRs due to SFR integration assumptions is to be considered on the second and third period.

During the second period, from 2040 to 2080 [T_1 = 28; T_1''= 68],

$$P_2 = \int_{T1}^{T_1'} \left(\frac{1}{30}t-\frac{28}{30}\right) e^{-0,02t}dt + \int_{T_1'}^{T_1''} \frac{1}{3} e^{-0,02t}\, dt \quad (D.1)$$

$$\boldsymbol{P_2' = \int_{T_1}^{T_1''} e^{-0,02t}\, dt - P_2} \quad (D.2)$$

During the third period, from 2080 to 2150: [T_1''= 68; T_2 = 138],

$$P_3 = \int_{T_1''}^{T_1'''} \left(\frac{1}{30}t - \frac{58}{30}\right) e^{-0,02t} dt + \int_{T_1'''}^{T2} e^{-0,02t}\, dt \quad \text{(D.3)}$$

$$\boldsymbol{P_3' = \int_{T_1''}^{T_2} e^{-0,02t}\, dt - P_3} \quad \text{(D.4)}$$

With $T_1 = 28$, $T'_1 = T_1+10 = 38$, $T''_1 = T'_1+30 = 68$, $T'''_1 = T''_1+20 = 88$, $T_2 = 138$.

As said in 4., changes are made on term C, which is the discounted cost of production during the second period in the case where R&D has been launched in 2012. In the endogenous model, the calculation remains the same for the second period [2040; 2080] but introduces a probability of a price drop in the third period [2080; 2150].

The cost of the second period is thus:

$$e^{(a_2-a_1)\times 27} Cost\ LWR_{100} * \left[P_2 \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\frac{s}{0,05}} (1+0,05p) f_p\,(p) dp + \int_{\frac{s}{0,05}}^{\infty} (1+s) f_p\,(p) dp\right] f_s(s) ds + P'_2 \int_{-\infty}^{\infty} (1+0,05p) f_p\,(p) dp\right] \quad \text{(D.5)}$$

The cost for this third period is however composed of the sum of two terms of cost:

- one using the same uranium price mean p_m as in the previous period, multiplied by the probability of not having competitive SFRs : this term represents the case in which SFRs were not competitive during the second period, and did not develop, having not influence in the predicted evolution of uranium price:

$$e^{(a_2-a_1)\times 27} Cost\ LWR_{100} * \int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}} f_p\,(p)dp\right] f_s(s)ds\left[P_3\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}}(1+0{,}05p)f_p\,(p)dp+\int_{\frac{s}{0,05}}^{\infty}(1+s)f_p\,(p)dp\right]f_s(s)ds+P'_3\int_{-\infty}^{\infty}(1+0{,}05p)f_p\,(p)dp\ \right]. \quad \text{(D.6)}$$

- the other using a lower uranium price mean p_m' (and a density probability function $f_{p'}$instead of f_p) multiplied by the probability of having competitive SFRs : this term represents the case in which SFRs were competitive during the second period, were integrated in the nuclear fleet and provoked a drop in uranium price:

$$e^{(a_2-a_1)\times 27} Cost\ LWR_{100} * \int_{-\infty}^{\infty}\left[\int_{\frac{s}{0,05}}^{\infty} f_p\,(p)dp\right] f_s(s)ds\left[P_3\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}}(1+0{,}05p)f_{p'}\,(p)dp+\int_{\frac{s}{0,05}}^{\infty}(1+s)f_{p'}\,(p)dp\right]f_s(s)ds+P'_3\int_{-\infty}^{\infty}(1+0{,}05p)f_{p'}\,(p)dp\right]. \quad \text{(D.7)}$$

There from the term C which consists of the sum of all these terms is:

$$C = e^{(a_2-a_1)\times 27} Cost\ LWR_{100} *$$

$$\left[P_2\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}}(1+0{,}05p)f_p\,(p)dp+\int_{\frac{s}{0,05}}^{\infty}(1+s)f_p\,(p)dp\right]f_s(s)ds+\right.$$

$$P'_2\int_{-\infty}^{\infty}(1+0{,}05p)f_p\,(p)dp+\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}} f_p\,(p)dp\right] f_s(s)ds\left[P_3\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}}(1+0{,}05p)f_p\,(p)dp+\right.\right.$$

$$\left.\int_{\frac{s}{0,05}}^{\infty}(1+s)f_p\,(p)dp\right]f_s(s)ds+P'_3\int_{-\infty}^{\infty}(1+0{,}05p)f_p\,(p)dp\ \Big] \quad +$$

$$\int_{-\infty}^{\infty}\left[\int_{\frac{s}{0,05}}^{\infty} f_p\,(p)dp\right] f_s(s)ds\left[P_3\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\frac{s}{0,05}}(1+0{,}05p)f_{p'}\,(p)dp+\int_{\frac{s}{0,05}}^{\infty}(1+s)f_{p'}\,(p)dp\right]f_s(s)ds+\right.$$

$$\left.\left.P'_3\int_{-\infty}^{\infty}(1+0{,}05p)f_{p'}\,(p)dp\right]\right]. \quad \text{(D.8)}$$

Conclusion

The purpose of this thesis was to assess the potential penetration of Generation IV Fast Reactor technology on the French and European market, within 2040. We have chosen to focus on investors, i.e. power generation companies, and to analyze their behavior regarding investments in generation capacities taking into account all technologies - coal, gas, hydropower, wind, solar - and not specifically nuclear. The goal is to take an investor's perspective when it comes to renew or extend installed capacity, and to understand what makes him choose a technology or a portfolio of technologies over another one. We have examined two research issues: first, we have sought to identify the drivers for investors' decisions on the European electricity market regarding investments in power generation capacities; and then, to assess how they affect the development of the European generation mix and the integration of Fast Reactors in this mix.

1 Summary

A multidisciplinary approach has been adopted to provide complementary insights on the investigated issue.

First, a historical analysis has allowed identifying past drivers for investment decisions in the capacities of electricity production and understanding how these drivers have evolved over time, from 1945 to the present day, in the specific context of Europe. By comparing the history of the European electricity markets with the successively dominant economic theories in this field, we could the differences between choices driven by long-term economic rationality as in economic theory, and actual behaviors of investors and governments. This article has thus identified the drivers for electricity investment and how these drivers have evolved over the six decades starting from 1945 up to now.

The first driver is <u>state policy</u>, which can follow economic theory but tends to be shaped by political issues, such as security of supply or environmental concerns. This historical analysis shows that, in the 1960s, national strategies used to be torn between economic rationality (importing cheap oil rather than using expensive domestic coal) and protection of national interests (local employment, energy independency). The paradigm clearly shifted to the protection of energy independency after the two oil crises in the 1970s, leading European power companies to ensure security of supply and energy independency at high costs. Starting from the 1990s, the recent urgency to reduce CO_2 emissions and to use renewables is calling on increasing intervention of states (e.g. in Germany or UK) and the EU regarding energy choices. Within the European scope, the state policy driver thus evolved from energy independency to environmental concerns.

The second driver is the relative availability of the resource or technology, taking into account the local nature of the resource and its price, together with the know-how it requires. In times of crisis, the availability of the resource or technology becomes crucial and its effects can exceed the effects of state policy. We can see that European countries have massively privileged local resources (such as coal in Germany) or the development of a locally well-mastered technology when local resources were poor (such as nuclear in France). This tendency was reinforced after the two oil crises in the seventies, leading European power companies to ensure security of supply and energy independency at high costs. In the end, rather than following long-term economic rationality to maximise profits, it thus seems that companies tend to seize short-term opportunities in order to ensure long-term security.

Thirdly, the market structure driver tends to emerge as a result from the liberalisation process. It can lessen the reach of state policy and thus makes investment coordination much more difficult. Besides, the liberalization of electricity markets in the European Union, more than twenty-five years ago, stems from a rationalization prescribed by new economic theories. However, it is now questioned, for it remains very heterogeneous, which complicates the goal of creating a large single market for electricity in the Union. Moreover, we see a recent re-centralization of energy policy in Europe, which takes the form of a new regulation mainly relating to climate and renewables. However, this re-regulation is different from centralized control experienced by all European electricity markets until the mid-1980s.

In the continuity of historical analysis of drivers, a more detailed investigation of investment drivers was conducted to go deeper in understanding investors' decision, using a strategic foresight method: structural analysis.

This chapter identifies the key drivers behind the choices of investors and construction scenarios for the European generation mix based on the development of these drivers in the future, adding new elements to the findings of the historical analysis: 1) policy (divided into climate policy and nuclear policy), 2) market drivers, 3) technical change and 4) company drivers, detailed in Table I.

N°	Variable	Related Driver
1	Carbon tax (€/tCO_2)	Policy Driver
2	CO_2 quota	
3	Feed-in tariffs for renewables (€/MWh)	
4	Green certificates for renewables	
5	Tenders for renewables	
6	Fiscal incentive for renewables	
7	Nuclear position	
8	Nuclear strike price (€/MWh)	
9	Stability of policy	
10	HHI concentration index	Market Driver
11	Development of grid and interconnections	
17	Corporate financing	
18	Project financing	
19	Hybdrid financing method (corporate and project financing)	
20	Other original financing method	
12	Construction costs (€/MW)	Technical Change Driver
13	Generation costs (€/MWh)	
14	Building period (year)	
15	Size of plant (MW)	
16	Load factor (%)	
21	Shareholding structure	Company driver
22	Market Capitalization	
23	Annual Production	
24	Generation Mix	
25	Market share	
26	Annual revenue	

Table VI: Decision variables for each driver

The results of structural analysis and scenario discussion show that pro-nuclear policies are not enough to promote nuclear development in Europe: business-as-usual scenarios are not favourable to SFRs; climate policy appears to be the *sine qua non* condition for further nuclear development. However, while nuclear policy seems stable, climate policy is endogenous and highly dependent on technical change. Surprisingly, the market driver is negligible compared with the two others. In the end, both strong and moderate pro-nuclear policies are compatible with SFR investment in the scenarios with low technical progress and strong climate policy, where nuclear is the only economically viable alternative ("climate constraint" scenarios). The scenarios of strong climate policy combined to a strong pro-nuclear policy assumption are also favourable to SFRs in a context of flourishing renewable ("totally green" scenarios). Three scenarios favourable to SFR investment have thus been identified regardless of the market driver; that is to say, they gather the necessary conditions for SFR investments.

Climate policy changes are thus determining for nuclear investment within our European scope. On a broader scale, the climate policy of Europe is decisive for the whole international climate policy:

the achievement of its objectives would be a catalyst for an international climate policy, whereas its failure would discourage further attempts to build an international climate policy.

Going further than structural analysis, a creation value approach combined to Design Structure Matrix and Quality Function Development Matrix methods has allowed building a tool replicating the behaviors of investors. First defining the expectations of all stakeholders involved in the investment decision, the approach then isolates the case of the power company and its expectations regarding the investment. The tool uses the formerly identified drivers to assess the compatibility of an investor (i.e. a power generating company) with a technology under the form of a compatibility index. In the three scenarios retained by structural analysis, technology choices are thus modeled for the companies in the scope under study with the compatibility index, and future generation mix are deducted. The result show that future nuclear development is even more bonded to state support than sensed in Chapter 3. Even with strong climate policy and no cost reduction of other technologies, without incentives from national governments, nuclear energy seems to see its share decreasing with little prospects of stepping into the next generation of nuclear reactors. France would be the only country where development of Generation IV could seem possible, while United Kingdom keeping its share of nuclear under 20%; even with a shift in nuclear stance and the apparition of moderate pro-nuclear policy in the 2015-2050 period, no nuclear investment would happen in Italy or Spain. Conversely, the presence of an incentive encourages growing shares of nuclear, slightly in France and up one third of generation in United Kingdom. It could reverse the trend in Spain and Italy by triggering non negligible investments resulting in a nuclear share around 10-15%. Generation VI deployment would thus be feasible with very favorable prospects in France and United Kingdom in 2040; in Spain and Italy, given the recent character of assessed nuclear investments, such industrial deployment would not be likely to happen quickly, but the possibility would still remain for later investments. These countries showing the main trends in Europe, the results can be extended to EU-27: the countries with steady involvement in nuclear following the trends of France and United Kingdom, the ones fully committed to a nuclear phase out following the identified trends of Germany, and the ones currently disengaged from nuclear energy but potentially versatile in their stance following the trends of Spain and Italy.

As a last step of our research, we completed our work by analysing investment choices one step ahead of the investment choice in a power plant: investment choice in a research program, and by focusing on nuclear technologies, in order to assess relative attractiveness of Generation IV SFR compared to current LWR. We narrowed down our research to the French case, where a Fast Reactor research program is on the run, and try to assess *a posteriori* the economic value of this research program from a long-term economic rationality point of view.

We developed a model based on the real options theory that compares the consequences of the two possible outcomes: with the SFR option (i.e. with the research option), and without. If the SFR option is available, the electricity operator could choose to integrate the technology in the fleet in 2040 or not, according to uranium prices and technology costs; if the SFR option is not available, the only choice would be to keep operating Generation III reactors.

Two key variables were chosen for the assessment of future fleet costs and relevant attractiveness comparison: the price of uranium and the overcost of Generation IV reactors compared to the previous generation. Uncertainty on both key variables was modeled through a probabilistic approach. As a result of the comparison carried out in this study, more economic value seems to lie in the research option. Sophisticating the model by taking into account the feedback effect of Generation IV development on the uranium market shows that the competitiveness of Generation IV reactors would even be beneficial for the competitiveness Generation III reactors, thus for the whole nuclear sector.

In the end, developing a research program for Fast Reactors is consistent with long-term economic rationality. The actual deployment of Fast Reactors in 2040 in Europe will depend on opportunity signals received by investors then. Two decisive necessary conditions appear: a pro-nuclear stance of the state associated with an incentive providing the necessary security for the investor, and the assertiveness and clarity of climate change mitigation policies. These two conditions have way more impact in investors' preferences than investment costs, financing methods, and liberalization of electricity market factors, which clearly shows the failure in achieving efficient competition on the European electricity market.

Climate policy changes are thus determining for nuclear investment within our European scope. However, the climate policy of Europe is strongly bonded to the whole international climate policy. On the on hand, it is a model, and the achievement of its objectives would set an example for an international climate policy. On the other hand, with no commitment of other countries, a strong policy in Europe would be meaningless; it is thus dependent on the results of future international climatic negotiations. Besides, leading a strong and coherent climate policy in Europe with no unified energy policy is difficult, as the current inefficiency of the EU ETS shows. Our results thus raise the question of the necessity to build a common energy policy associated with the climate policy in order to ensure its success.

2 Contributions and limits

The several methodological approaches used here have allowed identifying the drivers for electricity investment on the European market and assess necessary conditions for industrial development of future nuclear reactors. Compared to classic Cost-Benefit analysis, those complementary approaches allow drawing a more comprehensive picture of investment drivers by taking into account non-monetary factors and weighing their importance according to their interactions with one another. They can thus be beneficial for all stakeholders involved regarding the actions to be taken for their own interest:

- From a company's point of view, they provide explanations on both inner behaviors and competitor's behaviors
- From a policy maker's point of view, they provide useful insight to elaborate more relevant policy measures in order to trigger the expected reactions from companies.
- From market actors' point of view, they show what limits their impact on decisions.
- From a technology developer's point of view, they show the technical factors to work on and signals from other stakeholders to be watched carefully.

This study nevertheless has limits, beyond the methodological limits for each approach that have been acknowledged in every chapter already. Among technologies omitted in this study, some of them could start to play a more and more important role in the energy landscape within two decades: biomass, geothermy, carbon capture and storage and SMRs. Especially carbon capture and storage could change the attractiveness of fossil fuels, while the development of SFRs in the form of small modular reactors could change the analysis by making the technology easier to access for power companies- but would induce more grid development just like renewables.

There is also an indirect driver 'public acceptance of the technology' that was here included in the policy driver as the nuclear stance. The weight of this driver seems likely to keep growing in Europe and all over the world. Ever since the Fukushima accident in Japan in 2011 on March 11, and given the influence it has already had on some of the decisions of European countries, this parameter cannot be neglected anymore. Beside nuclear energy, it could also affect the development of other technologies, for instance the massive deployment of wind that seems to be possible could be contained because of public opposition to major landscape transformation.

Indeed, as the historical analysis showed, investment drivers are subject to change and sometimes brutal changes. The drivers identified for current choices and next decades in Europe are also likely to change quicker than expected in case of major events. It is thus necessary to bear in mind that in such cases.

3 Perspectives

Methodologically speaking, the approach could be replicated in several different contexts with more or less adaptation: the same question could have been applied other countries, leading to base the analysis on different drivers. It could also have been applied to a different power generation technology, leading to different favourable scenarios but keeping the same frame of study, or different technologies for other energy use than electricity (transportation, heating…), then demanding thorough adaptation in terms of drivers and stakeholders analysis.

From an international perspective, the same question could indeed have led to completely different results in other areas of the world. International SFR development is thus not bound to Europe only. Other drivers such as a strong electricity demand due to quick industrialization could create an environment favourable to SFRs. In emerging countries in Asia or South America, the main driver is a growing demand, often associated with a will to ensure energy independency and gain technological advancement. Such drivers could create an environment favourable to SFR even under circumstances described as unfavourable scenarios in Europe. It is the case of most countries interested in SFR mentioned in the introduction: Russia, China, India, Korea. In areas where industrialization has not yet printed the usual pattern of an electricity sector relying on a national grid, like Africa, future electricity markets could be build according to drastically innovative patterns and thus obey to very different drivers.

Personal publications

Publication in peer-reviewed journal

Article submitted in Revue Economique (July 2013): 'Economic assessment of R&D with real options in the field of fast reactors taking into account uncertainty on their competitiveness: the case of France', (N. Taverdet-Popiolek, B. Shoai Tehrani)

Article submitted in Energy Studies Review (November 2013): 'Three Investment Scenarios for Future Nuclear Reactors in Europe' (B. Shoai Tehrani, P. Da Costa)

Article submitted in Energy Studies Review (December 2013): 'Economic Thoughts and Investment Decisions on the European Electricity Market' (B. Shoai Tehrani, P. Da Costa)

Publication in International Conferences

2013, May 28-30:10th International Conference on the European Energy Market (EEM13), Stockholm, Sweden

2 Oral communications with publication in proceedings: '3 Investment Scenarios for Generation IV Nuclear Reactors' (B. Shoai Tehrani, P. Da Costa)

'Historical and theoretical approach of European Market: how does electricity investment evolve with historical context?' (B. Shoai Tehrani, D. Attias, J.-G. Devezeaux de Lavergne)

2013, March 20-22*:* International Conference on Renewable Energies and Power (ICREPQ'13), Bilbao, Spain.

Oral communication with publication in proceedings: 'Investment scenarios in low carbon electricity in Europe' (B. Shoai Tehrani, P. Da Costa)

2013, March 4-7*:* International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), Paris, France.

Oral communication with publication in proceedings: '3 Investment scenarios for Generation IV fast reactors' (B. Shoai Tehrani, P. Da Costa)

Poster with publication in proceedings: 'Why R&D for Generation IV reactors should be subsidized? A strictly economic point of view with real option theory' (N. Taverdet-Popiolek, B. Shoai Tehrani)

Seminars

2013, July 5*:* Electromobility Workshop 2013, Ecole Centrale Paris, France

Oral communication: 'Power Generation Investment Issues and Cross-Impacts with Electromobility'

2013, May 25*:* PhD Candidates' Seminar 2013, CEA Saclay, France

Oral communication: 'Power Generation Investment: an Approach of European Choices regarding nuclear'

2012, October 12: Workshop of the SAEE Student Chapter in ETH, in Zürich, Switzerland

Oral communication: '3 Investment scenarios for Generation IV fast reactors' (B. Shoai Tehrani, P. Da Costa)

2012, May 30*:* PhD Candidates' Seminar 2013, CEA Saclay, France

Poster: 'Electricity investments and development of power generation capacities: an approach of drivers for nuclear choices'. Distinguished by committee

2012, May 10*:* PhD Candidates' Seminar 2012, Ecole Centrale Paris, France

Poster: 'Electricity investments and development of power generation capacities: an approach of drivers for nuclear choices'

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