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# Variable and renewable energies and power system flexibility: the case of French region Occitanie

Théotime Coudray

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UNIVERSITÉ DE  
MONTPELLIER



# ENERGIES RENOUVELABLES INTERMITTENTES ET FLEXIBILITÉ DU SYSTÈME ÉLECTRIQUE : LE CAS DE LA RÉGION OCCITANIE

## VARIABLE AND RENEWABLE ENERGIES AND POWER SYSTEM FLEXIBILITY : THE CASE OF FRENCH REGION OCCITANIE

THÈSE DE DOCTORAT EN SCIENCES ÉCONOMIQUES

Préparée à l'Université de Montpellier  
**Ecole Doctorale d'Economie - Gestion : EDEG n°231**

### SOUS LA DIRECTION DE

Mme **Sandrine MICHEL**

Mr **Boris SOLIER**

Soutenue publiquement le 28 Février 2024

par

**Théotime COUDRAY**

### COMPOSITION DU JURY

Mme Carine STAROPOLI, Professeure des Universités - Univ. Rouen  
Présidente du jury

Mr Frédéric LANTZ, Professeur - IFP School  
Rapporteur

Mme Anna CRETI, Professeure des Universités - Univ. Paris Dauphine  
Rapporteuse

Mme Sandrine MICHEL, Professeure des Universités - Univ. Montpellier  
Directrice de thèse

Mr Boris SOLIER, Maître de Conférences - Univ. Montpellier  
Co-encadrant de thèse







# UNIVERSITE DE MONTPELLIER

Ecole Doctorale d'Economie-Gestion : EDEG N°231

Laboratoire Agriculture, Ressources et Territoires dans le  
Développement (ART-Dev, UMR 5281)

Chaire Economie du Climat (CEC)

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## THESE DE DOCTORAT

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**Théotime COUDRAY**

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OCCITANIE**

Présidente du jury : **Madame Carine STAROPOLI** – Professeure des Universités (Univ. Rouen)

Rapporteurs : **Madame Anna CRETI** – Professeure des Universités (Univ. Paris Dauphine)

**Monsieur Frédéric LANTZ** – Professeur (IFP School)

Directeurs de thèse : **Mme Sandrine MICHEL** – Professeure des Universités (Univ. Montpellier)

**M. Boris SOLIER** - Maître de Conférences (Univ. Montpellier)



*A mon chien Crouty Paty,*

*Qui ne m'aura été d'absolument aucune aide sur ce projet.*





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# ABSTRACT

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This thesis addresses the integration of Variable and Renewable Energies (VRE) in the Occitanie region of France, a pertinent issue in the broader context of the global energy transition. The study revolves around the critical question of managing power system flexibility in the face of increased VRE integration.

A hybrid deep-learning forecasting model is developed, combining time-series decomposition with Convolutional LSTM networks, to predict power system flexibility requirements. Subsequently, a cost-optimization model is introduced to explore flexibility sourcing from a spectrum of technologies. Last, a scenario analysis is conducted on future Occitanie power system flexibility. Using the cost-optimization model, we explore how can flexibility management can be performed under varying conditions.

The findings provide valuable insights into power system flexibility, emphasizing the strategic importance of technologies like hydropower, grid, and storage. The thesis contributes significantly to the field of energy system management and flexibility, offering both theoretical frameworks and practical methodologies that are relevant to current challenges and future developments in renewable energy integration.

**Keywords:**

Variable and Renewable Energies (VRE) ; Power System Flexibility ; Regional Power System Forecasting ; Optimization ; Scenario Analysis



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# RESUME

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Cette thèse aborde l'intégration des Energies Renouvelables Intermittentes (EnRI) dans le système électrique de la région française d'Occitanie, une question pertinente dans le contexte plus large de la transition énergétique. L'étude se concentre sur la question cruciale de la gestion de la flexibilité des systèmes énergétiques face à l'intégration croissante des EnRI.

Un modèle hybride de prévision par apprentissage profond est développé, combinant la décomposition de séries temporelles et les réseaux LSTM convolutifs, afin de prédire les besoins de flexibilité d'un système électrique donné. Ensuite, un modèle d'optimisation des coûts est introduit pour explorer l'approvisionnement en flexibilité à partir d'un spectre de technologies. Enfin, une analyse de scénario est menée sur le futur de la flexibilité du système électrique Occitan.

Les résultats fournissent des aperçus utiles sur la flexibilité du système électrique, soulignant l'importance stratégique de technologies telles que l'hydroélectricité, le réseau et le stockage. La thèse contribue de manière significative au domaine de la gestion et de la flexibilité des systèmes électriques, offrant à la fois des cadres théoriques et des méthodologies pratiques qui sont pertinentes pour les défis actuels et les développements futurs liés à l'intégration des EnRI.

**Mots-clés :**

Energies Renouvelables Intermittentes (EnRI) ; Flexibilité du Système Electrique ; Système Electrique Régional ; Prévision ; Optimisation ; Analyse de scénarios



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<b>ANN</b>	Artificial Neural Network
<b>ARIMA</b>	Autoregressive Integrated Moving Average
<b>BEV</b>	Battery Electric Vehicle
<b>CCGT</b>	Combined Cycle Gas Turbine
<b>CEEMDAN</b>	Complete Ensemble Empirical Mode Decomposition with Adaptive Noise
<b>CI</b>	Computer Intelligence
<b>DER</b>	Distributed Energy Ressources
<b>DSO</b>	Distribution System Operator
<b>EEMD</b>	Ensemble Empirical Mode Decomposition
<b>EMD</b>	Empirical Mode Decomposition
<b>IEA</b>	International Energy Agency
<b>IMF</b>	Intrinsic Mode Function
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>IRENA</b>	International Renewable Energy Agency
<b>LSTM</b>	Long-Short Term Memory
<b>MAPE</b>	Mean Absolute Percentage Error
<b>ODRE</b>	Open-Data Réseaux Energies
<b>P2P</b>	Peer-to-Peer
<b>P2X</b>	Power-to-X
<b>PHS</b>	Pumped-Hydro Storage
<b>PPE</b>	Programmation Pluriannuelle de l'Énergie
<b>PtG</b>	Power-to-Gas
<b>PV</b>	Photovoltaic

<b>REPOS</b>	Région à Energie Positive
<b>RL</b>	Residual Load
<b>RMSE</b>	Root Mean Squared Error
<b>RNN</b>	Recurrent Neural Network
<b>RPS</b>	Renewable Portfolio Standard
<b>RTE</b>	Réseau de Transport d'Electricité
<b>SNBC</b>	Stratégie Nationale Bas Carbone
<b>TSO</b>	Transmission System Operator
<b>V2G</b>	Vehicle-to-Grid
<b>VPP</b>	Virtual Power Plants
<b>VRE</b>	Variable and Renewable Energies





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# INTRODUCTION GENERALE

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## 1. Décarboner les systèmes électriques avec les énergies renouvelables intermittentes

Le 6<sup>ème</sup> Rapport d'Évaluation (AR6) de 2022 sur le Réchauffement Climatique, réalisé par le Groupe d'experts Intergouvernemental sur l'Évolution du Climat (GIEC), souligne l'urgence de réductions immédiates et significatives des émissions mondiales de gaz à effet de serre. Leurs modèles démontrent les impacts profonds sur les écosystèmes et les sociétés humaines si la température moyenne mondiale dépasse la limite de 1,5°C fixée par l'Accord de Paris. Les impacts varient entre des événements météorologiques extrêmes, la montée des niveaux de la mer, la diminution de la glace de mer Arctique, et la perte de biodiversité, qui sont prévus pour être nettement pires avec une augmentation de 2°C [GIEC, 2022]. Une atténuation substantielle de ces conséquences exige un changement radical dans nos modèles de production et de consommation d'énergie. Les systèmes énergétiques traditionnels basés sur les combustibles fossiles contribuent fortement aux émissions mondiales de carbone, représentant environ 73% [GIEC, 2022] des émissions totales de gaz à effet de serre. Étant donné la contribution considérable du secteur énergétique aux émissions mondiales, la transition vers des systèmes énergétiques plus propres et durables n'est pas seulement une option mais une nécessité pour la survie humaine.

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L'appel à une transition vers une énergie propre est une invitation à encourager les investissements dans des sources d'énergie décarbonées telles que l'hydroélectricité, l'énergie nucléaire ou les énergies renouvelables intermittentes. En effet, les objectifs climatiques impliquent que les pays devraient maintenant remplacer les technologies de production d'énergie à base de combustibles fossiles traditionnels par des technologies plus durables, c'est-à-dire des technologies qui émettent moins ou pas de dioxyde de carbone pendant le processus de production d'énergie. Ces technologies ont des exigences différentes et leur développement est inégal à travers le monde. Par exemple, l'hydroélectricité a été développée en Europe occidentale depuis le début du 20<sup>ème</sup> siècle et aujourd'hui, une grande partie du potentiel de cette méthode de production d'énergie a déjà été exploitée. D'autre part, l'énergie nucléaire est un moyen de production coûteux et technologiquement intensif, nécessitant des niveaux de sécurité très élevés, et dépend également du flux de ressources primaires (en particulier l'uranium) disponibles. Ainsi, cette technologie suscite de grands débats, même dans les pays qui l'ont adoptée tôt comme la France.

Enfin, les énergies renouvelables intermittentes telles que le photovoltaïque solaire et l'éolien gagnent du terrain depuis le début du 21<sup>ème</sup> siècle. Ces technologies sont très prometteuses en raison de l'abondance des ressources solaires et éoliennes, ainsi que de leur potentiel pour la production d'électricité sans émission. Cependant, elles suscitent également des débats, notamment concernant la disponibilité de ressources primaires rares nécessaires à leur construction, mais aussi pour la question complexe de l'intégration de la production intermittente dans les systèmes énergétiques qui sont historiquement conçus pour fonctionner avec une production contrôlable. Toutefois, selon le rapport World Energy Outlook 2022 de l'Agence Internationale de l'Énergie (AIE), le solaire photovoltaïque (PV) et l'éolien

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représentaient plus de 70% des ajouts totaux de capacités renouvelables dans le monde, soulignant leur rôle central dans la transition énergétique mondiale [AIE, 2022].

Le développement et le déploiement rapides de ces sources d'énergie renouvelable variables (VRE) peuvent être attribués à de nombreux facteurs, comprenant les progrès technologiques et la baisse des coûts, les politiques gouvernementales favorables et la sensibilisation croissante du public au changement climatique.

Commençons par examiner la relation complexe entre les avancées technologiques et la baisse des coûts. En effet, cette interaction a transformé les énergies renouvelables intermittentes d'une solution de niche en un acteur majeur du secteur énergétique mondial. En particulier, les coûts du solaire PV et de l'énergie éolienne ont connu une baisse remarquable au cours de la dernière décennie. Des percées en science des matériaux et en ingénierie ont conduit à des améliorations substantielles de l'efficacité et des performances des systèmes d'énergie solaire PV et éolienne. Pour le photovoltaïque solaire, des innovations dans la conception des cellules solaires et le développement de nouveaux matériaux, tels que les cellules solaires en pérovskite, ont considérablement augmenté les taux de conversion d'énergie [Al Ashouri et al., 2020]. De même, pour l'énergie éolienne, la conception de turbines plus grandes et plus efficaces, y compris celles avec une aérodynamique avancée et des tours plus hautes, a permis une meilleure capture de l'énergie éolienne [Zhang et al., 2020]. De plus, les progrès technologiques ont facilité l'augmentation de la production de panneaux solaires et de turbines éoliennes. Avec des volumes de fabrication plus importants, le coût par unité diminue de manière significative. Ce phénomène, connu sous le nom d'économies d'échelle, a permis la production de masse de composants d'énergie renouvelable, les rendant plus abordables pour les consommateurs, les entreprises et les services publics. Les économies d'échelle ont également été stimulées par des avancées dans les processus de



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fabrication et l'automatisation. L'ingénierie de précision et les chaînes de montage automatisées ont amélioré la qualité et la cohérence des composants d'énergie renouvelable tout en minimisant les coûts de main-d'œuvre. Cela a joué un rôle clé dans la compétitivité des énergies renouvelables par rapport aux sources d'énergie traditionnelles. Selon l'Agence Internationale des Énergies Renouvelables (IRENA), le coût moyen pondéré mondial de l'électricité issue du solaire PV à grande échelle a diminué de 85% entre 2010 et 2020, en faisant la technologie de production d'énergie la moins chère dans de nombreuses régions du monde. De même, les coûts de l'éolien terrestre ont diminué d'environ 56% pendant la même période, tandis que les coûts de l'éolien offshore ont connu une baisse de 63% [IRENA, 2021].

Deuxièmement, combinée à une urgence croissante de réduire les émissions de gaz à effet de serre, la mise en œuvre de politiques énergétiques favorables a joué un rôle crucial dans la réalisation d'économies de coûts et dans les avancées technologiques dans le domaine des énergies renouvelables. Ces politiques ont non seulement créé un environnement propice à l'innovation, mais ont également contribué à des réductions substantielles du coût des technologies énergétiques propres. Par exemple, considérons le cas de la politique 'Energiewende' de l'Allemagne. Cette initiative progressiste, visant à passer à une économie à faible émission de carbone, a introduit des tarifs d'achat généreux pour l'énergie solaire. Bien que ces incitations aient été initialement établies lorsque les coûts de la technologie solaire étaient plus élevés, elles ont été maintenues pour soutenir le secteur alors que les coûts diminuaient. Ce soutien politique a agi comme un catalyseur pour la baisse rapide du coût de la technologie PV au cours de la dernière décennie [REN21, 2021]. De même, l'engagement du Danemark à devenir neutre en carbone d'ici 2050 souligne l'impact du soutien politique. L'accent mis par le pays sur l'énergie éolienne, soutenu par des conceptions de turbines avancées et des solutions d'intégration au réseau, a conduit au développement de turbines

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éoliennes plus efficaces [AIE, 2019]. Cet investissement, piloté par la politique, dans les parcs éoliens offshore a été rendu possible grâce à la technologie avancée, illustrant ainsi l'interaction entre la politique et l'innovation. Il est important de noter que les agences gouvernementales collaborent souvent avec des experts de l'industrie pour développer des feuilles de route technologiques qui définissent l'avenir des technologies d'énergie renouvelable. Ces feuilles de route informent les décisions de politique gouvernementale et de financement, veillant à ce que le soutien soit dirigé vers les technologies les plus prometteuses et les plus impactantes. En résumé, les politiques énergétiques favorables ont été essentielles pour réaliser des économies de coûts et des avancées technologiques dans le domaine des énergies renouvelables. Ces politiques ont fourni le cadre nécessaire pour l'innovation, permis des objectifs énergétiques propres ambitieux, informé les cadres réglementaires, soutenu les efforts de plaidoyer et tracé des feuilles de route claires pour la planification des politiques, ce qui a finalement permis d'orienter les courbes d'apprentissage vers la baisse des coûts. La relation entre le soutien politique et la transition vers une énergie propre est donc cruciale, car elle démontre comment les politiques favorables ont non seulement suivi les avancées technologiques mais les ont activement façonnées et conduites.

Troisièmement, sensibiliser le public a été un catalyseur vital pour stimuler l'élan derrière l'adoption des énergies renouvelables. Les préoccupations environnementales ont été au premier plan des campagnes de sensibilisation du public, telles que le documentaire 'Une Vérité qui Dérange' d'Al Gore [Gore, 2006], mettant en lumière les conséquences environnementales de l'utilisation des combustibles fossiles, y compris la pollution de l'air et les émissions de carbone. La prise de conscience du changement climatique est en effet un aspect crucial de cette sensibilisation, comme l'a souligné le GIEC, qui a mobilisé l'opinion publique. La compréhension par le public du rôle des émissions de carbone dans le changement climatique a conduit à une plus grande demande de solutions énergétiques

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renouvelables qui réduisent les empreintes carbone [GIEC, 2022]. Les avantages pour la santé ont également été soulignés dans les campagnes de sensibilisation, comme les rapports 'State of the Air' de l'American Lung Association, qui ont attiré l'attention sur les maladies respiratoires et les problèmes de santé découlant de la pollution de l'air [American Lung Association, 2021]. De plus, les avantages économiques associés aux énergies renouvelables ont attiré l'attention du public, l'IRENA soulignant le rapport coût-efficacité des technologies renouvelables. Ces informations ont informé le public sur la création d'emplois, la réduction des factures d'énergie et la croissance économique associées aux investissements dans les énergies renouvelables. Cela s'est traduit par une demande des consommateurs, comme en témoigne la hausse des installations de panneaux solaires résidentiels, motivée par les propriétaires cherchant à réaliser des économies [Solar Energy Industries Association, 2021]. Cette prise de conscience accrue a exercé une pression publique sur les décideurs politiques, conduisant à un plaidoyer citoyen et à l'adoption de politiques énergétiques renouvelables favorables. Des exemples notables incluent les normes de portefeuille renouvelable (RPS) en Californie, influencées par la demande publique pour des sources d'énergie plus propres [California Energy Commission, 2021]. En résumé, ces exemples soulignent le rôle influent de la sensibilisation du public, reliant divers aspects et contribuant au changement mondial vers l'adoption de l'énergie renouvelable. Cette prise de conscience accrue a façonné les perceptions du public, influencé le comportement des consommateurs, inspiré des changements politiques et nourri un sentiment de responsabilité partagée pour la transition vers un avenir énergétique plus propre et durable.

## 2. Le problème de la flexibilité

Malgré ces tendances positives, l'intégration d'une part élevée de VRE dans le système électrique présente des défis notables en raison de leur variabilité et incertitude inhérentes. En effet, l'électricité est souvent considérée comme un bien non stockable, ce qui se traduit par une contrainte d'équilibre entre l'offre et la demande à tout moment. Cette contrainte d'équilibre constante a été formulée sous les lois de Kirchoff, qui généralisent l'idée de conservation de la charge au sein de tout système électrique donné.

Pendant ce temps, l'intermittence de la lumière du soleil et du vent implique que la production d'énergie solaire PV et éolienne fluctue sur différentes échelles de temps, des changements instantanés aux variations à moyen et long terme, c'est-à-dire de secondes à saisons. De telles fluctuations introduisent des contraintes supplémentaires sur la contrainte initiale d'équilibrage de la charge, nécessitant ainsi des mesures efficaces pour équilibrer l'offre et la demande. Si la contrainte initiale d'équilibrage de la charge a été bien étudiée dans la littérature académique, l'émergence des VRE implique de nouvelles contraintes dues à leur variabilité et intermittence inhérentes, qui seront notre point focal dans cette thèse.

Pour être plus précis, le problème de sensibilité aux conditions initiales, qui stipule que de petites variations dans les conditions de départ d'un système complexe peuvent conduire à des résultats ou des trajectoires significativement différents au fil du temps, rend l'exercice de prédiction de la météo avec une précision parfaite une tâche irréalisable. La production des VRE, qui dépend des conditions météorologiques, est donc considérée comme difficile à prévoir. Cette dépendance aux conditions météorologiques signifie également que la production des VRE n'est pas contrôlable, ce qui introduit un tout nouveau paradigme pour la génération d'électricité qui reposait auparavant sur des moyens de production contrôlables tels que les centrales électriques à charbon ou à gaz. Les VRE peuvent donc être la source de

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problèmes techniques sur le système électrique, ainsi que d'une forte volatilité sur les marchés de l'électricité [Nicolosi, 2010 ; Hirth, 2013 ; Benhmad et Percebois, 2018a,b]. Par conséquent, de nombreux chercheurs et acteurs du secteur affirment que les systèmes électriques intégrant de plus en plus de VRE doivent également être de plus en plus flexibles [Holttinen et al., 2013 ; Oleinikova et Obushevs, 2015 ; Kondziella et Bruckner, 2016 ; Richard Druce et al., 2016].

### A. Définir la flexibilité

La flexibilité est un mot-valise qui englobe de nombreuses idées liées à l'adéquation entre la charge et la génération d'électricité à tout moment. Une définition générale de la flexibilité d'un système électrique est sa « capacité à faire face aux changements dans la génération ou la consommation d'électricité » [Hubert et al., 2014]. Dans cette optique, la flexibilité du système électrique est la capacité inhérente et dynamique d'un réseau électrique à s'adapter rapidement, de manière transparente et efficace aux fluctuations continues à la fois dans la génération et la consommation d'électricité. Elle est inhérente et dynamique en ce sens que la flexibilité n'est pas une caractéristique externe qui peut être ajoutée ou retirée à volonté. C'est une caractéristique intrinsèque profondément intégrée dans l'infrastructure et le cadre opérationnel du réseau. Cette capacité n'est pas statique mais évolue et s'adapte continuellement aux conditions et exigences changeantes. Ainsi, la flexibilité exige une réponse rapide aux changements de génération et de consommation, ce qui signifie que les opérateurs de réseau doivent être capables de faire des ajustements en temps réel pour équilibrer l'offre et la demande, minimisant les perturbations et maintenant la stabilité du réseau.

Cependant, la flexibilité va au-delà de la simple réponse pour englober l'efficacité. Le réseau doit s'adapter d'une manière qui minimise les pertes d'énergie et maximise l'utilisation

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efficace des ressources renouvelables et non renouvelables. Globalement, le but ultime de la flexibilité du système électrique est de garantir que l'électricité est livrée de manière constante et fiable aux utilisateurs finaux sans interruptions ou perturbations, au moindre coût.

En fait, le concept de flexibilité implique divers aspects temporels, chacun étant lié à une question concrète. Du temps réel au court terme (c'est-à-dire, de quelques minutes à quelques heures), la flexibilité est principalement requise pour l'équilibrage du réseau [Lannoye et al., 2012]. Du jour au lendemain à la semaine à venir (c'est-à-dire, à moyen terme), la flexibilité fera référence à la capacité des producteurs et des participants au marché à adapter soit la programmation optimale des unités de génération, soit la tarification de l'électricité aux variations de charge et de génération prévues [Shaaban et al., 2018 ; de Lagard et Lantz, 2018]. Enfin, sur des échelles de temps plus longues, comme les mois ou les années, l'adéquation entre la demande et la production d'électricité nécessitera la programmation des unités de production, la construction de nouvelles installations ou capacités de stockage, la conception de politiques énergétiques spécifiques ainsi que des investissements dans le réseau pour suivre les tendances de charge à long terme ou les variations saisonnières. Cette idée peut être référée comme la flexibilité à long terme [Esteban et al., 2012 ; Steinke et al., 2013 ; Ma et al., 2013 ; Heleno et al., 2015 ; Holttinen et al., 2016].

Pour mieux illustrer ce à quoi la flexibilité fait référence, il peut être utile de regarder les mécanismes existants et futurs conçus pour assurer une adéquation constante entre la production et la demande d'électricité. Lund et al. (2015) passent en revue les mesures de flexibilité qui permettraient d'intégrer de grandes parts d'énergies renouvelables variables (VRE) dans les systèmes électriques. Étant donné qu'il existe de nombreuses mesures, ils proposent une classification allant des mesures de réponse à la demande aux mesures relatives aux marchés de l'électricité. Afin de simplifier la catégorisation et de mieux représenter le

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champ d'action des solutions de flexibilité, nous proposons de classer les solutions existantes et en développement en trois catégories principales, qui sont simplement :

- Les solutions technologiques
- Les solutions de réseau
- Les solutions de marché

La plupart des **solutions de flexibilité technologiques**, comme les réserves tournantes ou les unités de génération contrôlables (par exemple, les centrales alimentées en combustibles fossiles), sont déjà utilisées aujourd'hui, car la contrainte d'équilibrage de la charge est une caractéristique historique de tous les systèmes électriques. [Ortega Vasquez et Kirschen, 2007 ; Jenkins et al., 2018] En réponse aux nouvelles contraintes introduites par les VRE, de nouveaux types de solutions de flexibilité technologique émergent également. Par exemple, les technologies de stockage d'électricité à grande échelle (par exemple, le stockage hydroélectrique par pompage (PHS), les volants d'inertie, les supercondensateurs, les batteries stationnaires ou le Power to X) font également partie des options de flexibilité technologique, mais la majorité d'entre elles sont encore en phase de développement initial [Denholm et Hand, 2011 ; Schill, 2014 ; Fuel Cell and Hydrogen Joint Undertaking (FCHJU), 2015, Blanco et Faaij, 2018 ; Percebois et Pommeret, 2019]. Enfin, certaines options de flexibilité technologique sont liées aux technologies VRE elles-mêmes. La production de VRE peut en effet être réduite en faisant tourner les pales des éoliennes, par exemple [Bongers et al., 2019]. La répartition géographique des capacités VRE peut également être classée comme une solution de flexibilité liée à la technologie, car elles peuvent être distribuées sur de vastes territoires pour bénéficier de différentes conditions météorologiques locales [Sarafidis et al., 1999 ; Krakowski et al., 2016]. Enfin, les technologies qui permettent une meilleure prévision de la production des VRE peuvent également être ajoutées à la catégorie des solutions de

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flexibilité liées à la technologie, car ces techniques sont essentielles pour évaluer les besoins en flexibilité d'un système électrique donné.

La deuxième catégorie concerne les **développements du réseau**, tant au niveau de la transmission que de la distribution, qui peuvent être mis en œuvre pour éviter les congestions (par exemple, les extensions de capacité du réseau) ou pour bénéficier de différentes conditions météorologiques locales (par exemple, les interconnexions) [Vito et al., 2017 ; Karimi Arpanahi et al., 2020]. Il convient de mentionner que les réseaux peuvent adopter diverses formes, allant des réseaux nationaux traditionnels dans lesquels les lignes de transmission sont vitales pour transporter l'électricité sur de longues distances, aux micro-réseaux qui permettent aux communautés énergétiques locales, au commerce pair à pair et aux ajustements fins de la charge et de la génération pour favoriser la flexibilité. L'agencement des réseaux à échelle inférieure et leur relation avec le réseau supranational centralisé sont complexes et délicats, car la décentralisation des décisions vers les niveaux inférieurs du réseau peut impacter le fonctionnement de l'ensemble du système.

Enfin, dans la catégorie des **solutions de marché**, nous incluons tous les mécanismes de marché permettant un appariement plus rapide et plus adaptatif entre la charge et la production (par exemple, les contrats intra-journaliers sur le marché de gros, le marché de capacité) et une meilleure gestion de la demande (par exemple, le marché de la réponse à la demande) [Sharifi et al., 2017 ; Villar et al., 2018]. Il est à noter que ce type de solutions de flexibilité repose le plus souvent sur une technologie spécifique, soit la communication dans le cas des contrats intra-journaliers, soit les technologies de production pour le marché de



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capacité. La forme institutionnelle d'un marché est cependant le dénominateur commun pour ces solutions de flexibilité.

Dans le tableau 1, nous proposons de présenter les différentes solutions de flexibilité, leur temps d'activation, l'échelle de temps pendant laquelle elles peuvent être utilisées et leur maturité actuelle. Le tableau utilise la classification décrite ci-dessus et inclut des sous-catégories pour les solutions liées à la technologie, car elles sont nombreuses et différentes par nature. Comme présenté dans le tableau, les solutions liées à la technologie sont le plus souvent utilisées pour l'équilibrage à court terme car leur temps d'activation est généralement très rapide. À l'opposé, les besoins en flexibilité à long terme sont le plus souvent adressés par des investissements à grande échelle, tels que les interconnexions de réseaux. Ce tableau représente un panorama des options de flexibilité et de leurs principales caractéristiques à l'heure actuelle, et sera sujet à de nouvelles entrées à mesure que la flexibilité deviendra un enjeu clé pour les systèmes électriques intégrant de grandes parts de VRE.

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Solutions de flexibilité	Temps d'activation	Flexibilité offerte	Maturité
<b>Solutions technologiques</b>			
<u>Réserves de stabilité</u>			
Réserve primaire	< 30 secondes	Très court terme	En utilisation
Réserve secondaire	Entre 30 secondes et 15 minutes	Très court terme	En utilisation
Réserve primaire	Entre 30 minutes et 2 heures	Court-terme	En utilisation
<u>Production pilotable</u>			
Hydraulique de haute chute	En quelques minutes	Court, moyen et long terme	En utilisation
Centrales nucléaires	1-5% capacité/min de taux de rampe	Court, moyen et long terme	En utilisation
OCGT	20% capacité /min de taux de rampe	Court et moyen terme	En utilisation
CCGT	5-10% capacité /min de taux de rampe	Court et moyen terme	En utilisation
Centrales au charbon	1-5% capacité /min de taux de rampe	Court et moyen terme	En utilisation
Turbines à combustion	1-5% capacité /min de taux de rampe	Court et moyen terme	En utilisation
Centrales au biocarburant	1-5% capacité /min de taux de rampe	Court et moyen terme	En développement
<u>Liées aux VRE</u>			
Interruption	En quelques minutes	Court terme	En utilisation
Répartition géographique	Mois	Long terme	En utilisation et développement
Amélioration de la prévision	Entre quelques minutes et quelques heures	Très court à long terme	En utilisation et développement
<u>Stockage</u>			
Volants d'inertie	En quelques minutes	Très court à court terme	En développement
Batteries stationnaires	En quelques minutes	Très court à court terme	Développement très précoce
Supercapaciteurs	En quelques minutes	Très court à court terme	Développement très précoce
Vehicle-to-Grid	Entre quelques minutes et quelques heures	Très court à court terme	Développement très précoce
Pompage hydraulique	En quelques minutes	Court, moyen et long terme	En utilisation
Stockage par pompage de chaleur	En quelques minutes	Court terme	En développement
Stockage par air comprimé	En quelques minutes	Court à moyen terme	Développement précoce
Power-to-X	En quelques minutes	Court, moyen et long terme	Développement très précoce
Solaire concentré	En quelques minutes	Court terme	Développement précoce
<b>Solutions de réseau</b>			
Extension de capacité	Mois à années	Long terme	En utilisation
Interconnexions	Années	Très long terme	En utilisation et développement
<b>Solutions de marché</b>			
Effacement	En quelques minutes	Très court à long terme	En utilisation
Marché de capacité	En quelques minutes	Court à long terme	En utilisation
Contrats infra-journaliers	En moins d'une heure	Court-terme	En utilisation
Certificat d'Efficacité Energétique	Mois	Long-terme	En utilisation

Tableau 1. Classification des solutions de flexibilité existantes et en développement

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Atteindre des niveaux élevés de flexibilité n'est pas sans poser de problèmes. L'un des principaux obstacles réside dans le fait que la plupart des systèmes électriques dans le monde ont été conçus et exploités sur la base de ressources prévisibles et contrôlables, principalement des centrales électriques à base de combustibles fossiles. Avec l'augmentation récente des prix des combustibles fossiles (en particulier le gaz naturel), ce paradigme pourrait rapidement évoluer vers l'utilisation principale de sources renouvelables pour assurer la production de base. Cependant, l'intégration d'une grande quantité de VRE introduit de nouvelles dimensions de variabilité et d'incertitude, que les systèmes électriques traditionnels peuvent ne pas être bien équipés pour gérer. Cela nécessite une transformation significative de la manière dont les systèmes électriques sont conçus, exploités et régulés.

En effet, l'augmentation des capacités en VRE implique le passage de réseaux traditionnels organisés autour d'une production et d'une prise de décision centralisées à un mode d'exploitation plus décentralisé du système électrique. Comme la production des VRE est répartie sur l'ensemble du territoire, ce nouveau type de production décentralisée nécessite une approche plus granulaire lorsqu'il s'agit de gérer les flux d'électricité le long du réseau.

Une approche potentielle pour gérer cette transition est d'adopter une perspective régionale sur la flexibilité du système électrique. Les systèmes électriques régionaux peuvent être un moyen de représenter des parties du système électrique national basé sur une division administrative du territoire. Cette approche est donc une nouvelle façon de considérer certaines régions du système électrique national et peut être à la fois motivée par et un outil pour mettre en œuvre des politiques énergétiques locales. En effet, cette représentation régionale pourrait potentiellement offrir de meilleures opportunités pour exploiter les ressources locales de flexibilité, telles que le stockage d'énergie distribué et l'effacement. Cependant, passer d'une représentation nationale à une représentation régionale du système électrique implique un changement dans l'équilibre du pouvoir et des responsabilités entre

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différents acteurs, et soulève des questions autour des problèmes de sécurité, de fiabilité et d'équité du système électrique.

Cela introduit un nouvel ensemble de défis et de complexités, et constitue donc le cœur de notre question de recherche : **À quoi pourrait ressembler une gestion régionale de la flexibilité du système électrique ?** Pour répondre à cela, il est nécessaire d'explorer le fonctionnement des systèmes électriques nationaux, ainsi que le rôle potentiel et l'impact des systèmes électriques régionaux au sein de ceux-ci.

### B. Une nouvelle approche pour l'intégration des VRE avec l'idée d'un système électrique régional

Le système électrique conventionnel repose sur une génération centralisée dans de grandes centrales électriques, avec la transmission de l'électricité sur de longues distances jusqu'aux centres de charge. Cette manière de fonctionner centralisée et historique est due à plusieurs arguments issus de la théorie économique. L'un des principes fondamentaux motivant cette approche est le concept d'économies d'échelle. Ce principe suggère qu'à mesure que l'échelle de production augmente, le coût moyen par unité de production diminue. En conséquence, le coût marginal d'une unité supplémentaire de demande en énergie devient nul. Dans le contexte de la production d'électricité, les centrales électriques centralisées, souvent alimentées par du charbon, du gaz naturel ou des sources nucléaires, sont généralement grandes et bénéficient des économies d'échelle. Ces grandes installations peuvent générer de l'électricité à un coût inférieur par unité que des générateurs plus petits et décentralisés. Cet avantage économique a historiquement rendu la production d'énergie centralisée plus rentable. De plus, la nature capitaliste des technologies conventionnelles de production d'énergie, telles que les centrales à charbon ou nucléaires, rend plus faisable pour un nombre limité de

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grandes entités, telles que les services publics ou les entreprises d'électricité, d'investir dans ces installations et de les exploiter. Les coûts initiaux élevés en capital et les longues périodes de retour sur investissement sont mieux adaptés à une propriété centralisée, où les organisations peuvent répartir ces coûts dans le temps. En outre, la théorie économique reconnaît également le rôle de la réglementation et de l'intervention gouvernementale dans la formation des structures industrielles. Historiquement, les cadres réglementaires favorisaient souvent les services publics centralisés en raison des économies d'échelle perçues et du besoin d'investissements en infrastructure. Cet environnement réglementaire a encouragé le développement de grandes centrales électriques et de réseaux électriques centralisés. Enfin, les installations de production d'énergie centralisées sont bien adaptées à l'intégration dans des réseaux électriques centralisés, dont la structure de coûts implique une position de monopole naturel. Cela permet une transmission et distribution efficaces de l'électricité sur de longues distances pour répondre aux besoins d'une large population ou région. Les réseaux centralisés peuvent optimiser l'allocation de l'électricité provenant de diverses sources, y compris les centrales électriques, aux consommateurs, réduisant les pertes de transmission et améliorant la fiabilité globale du réseau. Cependant, l'avènement des VRE a ajouté une caractéristique décentralisée à la production d'énergie. Cette nature décentralisée de la production d'énergie pose des défis au réseau conventionnel, y compris le maintien de la stabilité du système et la garantie de la qualité de l'énergie.

En réponse à ces défis, le concept de systèmes électriques régionaux suscite de l'attention. Contrairement au système électrique national conventionnel, une représentation régionale du système électrique peut permettre une prise de décision plus agile et réactive pour accommoder la variabilité de la production de VRE localisée. Les systèmes électriques régionaux peuvent permettre une prise de décision et une gestion des ressources plus

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localisées, ce qui pourrait potentiellement débloquer des opportunités uniques pour renforcer la flexibilité du système électrique. Par exemple, les ressources énergétiques distribuées telles que le stockage à petite échelle, l'effacement et la production d'énergies renouvelables locales pourraient être gérées plus efficacement à l'échelle régionale [Hoppmann et al., 2014]. À mesure que les VRE augmentent leur part dans le mix énergétique, les interconnexions et la coordination entre les systèmes électriques nationaux et régionaux deviennent encore plus significatives, et comprendre leurs dépendances mutuelles est vital pour un fonctionnement fiable et efficace du système [Hirth et Ziegenhagen, 2015].

Les systèmes électriques régionaux décentralisés, bien qu'offrant divers avantages, présentent également des inconvénients. Gérer un réseau décentralisé avec un mélange diversifié de sources d'énergie distribuées peut être complexe. Il nécessite souvent des systèmes de contrôle et de communication sophistiqués pour assurer un fonctionnement fluide, surveiller les flux d'énergie et répondre aux perturbations du réseau. De plus, intégrer des systèmes décentralisés dans un réseau régional ou national plus large peut être techniquement difficile. Assurer la compatibilité et la stabilité lors de la connexion de diverses ressources distribuées peut nécessiter des investissements supplémentaires, et les réglementations et politiques existantes conçues pour les réseaux centralisés peuvent ne pas être bien adaptées aux systèmes décentralisés. Adapter les cadres réglementaires pour accueillir la production et la distribution d'énergie décentralisées peut également être un processus long et complexe. Enfin, coordonner la maintenance et les réparations à travers un réseau décentralisé avec une multitude d'actifs distribués peut être exigeant sur le plan logistique. Assurer la fiabilité et la sécurité de ces systèmes nécessite des procédures de maintenance efficaces et du personnel qualifié.

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Ainsi, le développement et l'exploitation de systèmes électriques régionaux au sein de systèmes électriques nationaux nécessitent une considération attentive de leurs interdépendances techniques, économiques et institutionnelles. Techniquement, la nature interconnectée des systèmes électriques implique que les opérations d'un système électrique régional peuvent avoir des effets sur le système électrique national plus large, et vice versa. En effet, puisque les systèmes électriques régionaux sont interconnectés, une panne ou un défaut dans une partie du système peut rapidement se propager, causant potentiellement des pannes étendues à travers tout le système. De plus, ces sous-systèmes peuvent conduire à un point unique de défaillance, les rendant vulnérables aux catastrophes naturelles, aux cyberattaques ou aux défaillances d'équipement qui peuvent entraîner des conséquences catastrophiques. Économiquement, les coûts et les avantages associés aux ressources de flexibilité régionales doivent être évalués dans le contexte plus large de l'opération du système électrique national. Les implications économiques de ce changement de point de vue sont multiples. D'une part, la production localisée peut réduire les pertes de transmission et améliorer l'efficacité du réseau, menant à des économies de coûts potentielles. Elle peut également renforcer la sécurité énergétique en réduisant la dépendance aux lignes de transmission à longue distance. D'autre part, les coûts initiaux des ressources distribuées et la nécessité de moderniser le réseau pour accueillir la génération variable peuvent augmenter les coûts globaux. De plus, les zones urbaines, par exemple, ont souvent une demande d'électricité plus élevée en raison de populations plus denses et d'activités industrielles, tandis que les régions rurales peuvent avoir des niveaux de consommation plus faibles. En raison de la politique énergétique française de tarification égalitaire, il est important de noter que les zones à forte densité de population subventionnent le développement du réseau électrique dans les zones rurales. Dans un système électrique centralisé, l'électricité peut être produite efficacement dans de grandes centrales électriques et transmise sur de longues distances pour

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répondre à ces demandes variables. Comparativement, les coûts de modernisation du réseau régional pour satisfaire ces besoins variables peuvent être plus élevés. Institutionnellement, de nouvelles formes de gouvernance et de cadres réglementaires peuvent être nécessaires pour permettre l'intégration et l'exploitation des systèmes électriques régionaux [Roelich et al., 2015].

Ces considérations nous guident vers la compréhension des politiques énergétiques régionales. Ces politiques énergétiques se réfèrent à un ensemble spécifique de règles, de réglementations et de stratégies conçues au niveau régional pour guider la production, la distribution et la consommation d'énergie. Les politiques énergétiques régionales présentent plusieurs avantages, ce qui les rend intéressantes à étudier dans le contexte de la flexibilité des systèmes électriques. D'abord, les politiques énergétiques régionales peuvent être finement ajustées pour répondre aux caractéristiques uniques et aux défis d'une zone particulière. Cette granularité permet aux décideurs de concevoir des solutions de flexibilité spécifiquement adaptées au paysage énergétique local, en tenant compte de facteurs tels que la disponibilité des ressources renouvelables, les contraintes d'infrastructure et les schémas de demande régionaux. De plus, en se concentrant sur les politiques énergétiques régionales, les décideurs peuvent optimiser l'utilisation des ressources énergétiques locales. Par exemple, les régions avec un fort potentiel solaire peuvent accentuer la production et l'intégration de l'énergie solaire dans leurs stratégies de flexibilité, tandis que les régions dotées de ressources éoliennes importantes peuvent privilégier les solutions d'énergie éolienne. Dans d'autres cas, les régions disposant de ressources géothermiques peuvent développer cette forme de récolte d'énergie, tandis que les régions qui ne possèdent pas de sources renouvelables significatives peuvent adapter leur infrastructure de réseau pour bénéficier de régions voisines avec des potentiels plus élevés. Cette approche centrée sur les ressources améliore l'efficacité globale



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et la durabilité du système énergétique. En outre, les politiques régionales peuvent faciliter l'alignement de l'infrastructure énergétique avec les besoins en flexibilité. Cela inclut la planification et les investissements dans l'amélioration du réseau, les installations de stockage d'énergie et les programmes de gestion de la demande adaptés aux besoins spécifiques de la région. Un tel alignement assure que les développements d'infrastructure sont synchronisés avec les objectifs énergétiques régionaux. De plus, les politiques énergétiques régionales peuvent stimuler le développement économique local en favorisant la croissance des industries liées à l'énergie et la création d'emplois. Par exemple, les régions peuvent inciter au développement de projets d'énergie renouvelable, attirant des investissements et créant des opportunités d'emploi. Enfin, différentes régions peuvent avoir des priorités et des préoccupations environnementales variées. Les politiques régionales peuvent prendre en compte ces facteurs environnementaux, garantissant que les solutions de flexibilité minimisent les impacts négatifs sur les écosystèmes locaux tout en maximisant l'intégration des énergies renouvelables intermittentes [Kern et Bulkeley, 2009].

Un exemple marquant de politique énergétique régionale se trouve dans l'État de Californie, aux États-Unis. Reconnaisant le potentiel significatif de l'énergie renouvelable dans l'État, la Californie a mis en place une norme ambitieuse de RPS qui exige que les services publics obtiennent 60 % de leur énergie de sources renouvelables d'ici 2030 et vise un secteur de l'électricité entièrement exempt de carbone d'ici 2045 [California Energy Commission, 2021]. Cette politique a été un moteur important de la croissance de l'énergie renouvelable de l'État, qui représentait 49 % de la production totale d'électricité en 2022, bien plus que la moyenne nationale de 20 % [U.S. Energy Information Administration (EIA), 2023]. Pour aborder la question de la flexibilité du système électrique, la Californie a introduit des mandats et incitations spécifiques pour promouvoir les technologies de stockage

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d'énergie, qui jouent un rôle crucial dans l'amélioration de la flexibilité du système électrique. Les objectifs de stockage de l'État exigent que les services publics acquièrent une certaine capacité de stockage d'énergie, aidant à lisser les fluctuations de la production d'énergie renouvelable et à soutenir la stabilité du réseau. De plus, la Californie a également donné la priorité aux programmes de réponse à la demande dans le cadre de sa stratégie de flexibilité. Ces programmes permettent aux consommateurs d'ajuster leur consommation d'électricité pendant les périodes de forte demande ou en réponse aux besoins du réseau, réduisant ainsi la pression sur le système et améliorant sa flexibilité. En matière d'adaptation du réseau, la Californie a investi dans des initiatives de modernisation du réseau. Ces efforts comprennent la mise à niveau de l'infrastructure du réseau, la mise en œuvre de technologies avancées de gestion du réseau et l'amélioration de la résilience du réseau pour mieux gérer la génération variable.

Un autre exemple de politique énergétique régionale se trouve dans la manière dont la région Provence-Alpes-Côte d'Azur, dans le sud de la France, accommode l'augmentation des capacités PV sur son territoire. Bien que le PV ne contribue qu'à environ 10 % de la production d'électricité renouvelable en France, des objectifs ambitieux ont été fixés pour multiplier par cinq la capacité PV d'ici 2028 et par dix d'ici 2030 dans la région Provence-Alpes-Côte d'Azur. Cependant, cette croissance ne devrait pas nuire aux zones agricoles ou naturelles. Pour guider le développement des projets PV, un cadre régional a été établi, mettant l'accent sur les PV installés sur les toits et les abris de stationnement et fournissant des orientations pour les installations PV au sol. Pour les projets PV au sol, une grille d'évaluation de la sensibilité priorise les zones de développement, en considérant les zones interdites, les zones à hauts enjeux, les zones à enjeux modérés et les zones privilégiées en fonction de divers facteurs. Cela fournit un exemple de la manière dont les politiques énergétiques

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régionales peuvent prendre en compte les facteurs environnementaux dans la poursuite d'une transition énergétique plus large [DREAL PACA, 2019].

Bien que le sujet prenne de l'ampleur, il convient de noter que les politiques énergétiques régionales sont un outil émergent qui accompagne les initiatives nationales pour la transition énergétique. En effet, c'est le développement même des VRE qui rend l'approche régionale utile en raison de leur nature décentralisée, et ce développement est récent dans la plupart des systèmes énergétiques. Il est donc compréhensible que seuls quelques exemples pertinents de politiques énergétiques régionales réussies puissent être trouvés. Cela est dû à plusieurs facteurs, le principal étant que les systèmes énergétiques régionaux sont des représentations de parties d'un système énergétique national ou supranational plus large. Ce type de représentation est basé sur une découpe administrative du territoire national, qui peut varier d'un pays à l'autre. Par exemple, une région en France ne signifie pas la même chose qu'un État aux États-Unis ou un Land en Allemagne, car ils n'ont pas les mêmes pouvoirs et responsabilités politiques et administratifs. Une autre raison est que contrairement aux politiques énergétiques nationales, souvent publiées dans des documents officiels gouvernementaux, les politiques régionales peuvent ne pas être accompagnées de suffisamment de sources d'information, par exemple en ce qui concerne la méthodologie utilisée pour leurs études, comme c'est le cas pour le scénario REPOS 2050. C'est encore pire pour les données sur les systèmes énergétiques régionaux ou les politiques énergétiques, qui ne sont pas facilement disponibles ou centralisées. Même lorsque les informations sont disponibles, elles peuvent être fragmentées sur plusieurs sources, y compris les sites Web des gouvernements régionaux, les institutions de recherche et les rapports, rendant la compilation d'un aperçu complet chronophage. Enfin, la diversité des outils utilisés dans les politiques énergétiques régionales peut les rendre difficiles à analyser de manière comparative. En effet, les politiques énergétiques régionales peuvent adopter plusieurs mécanismes pour promouvoir

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l'énergie renouvelable et la flexibilité des systèmes énergétiques. Cela peut inclure des incitations financières directes (telles que des tarifs d'achat garantis, des crédits d'impôt), des mesures réglementaires (telles que des normes de portefeuille renouvelable, la mesure nette) et des mécanismes basés sur le marché (tels que des systèmes de certificats d'énergie renouvelable, la tarification du carbone). Le choix des mécanismes politiques dépend de divers facteurs, notamment la disponibilité des ressources en énergie renouvelable locales, l'infrastructure énergétique existante et les conditions du marché local [Couture et al., 2010].

Il convient de noter que le financement national et européen joue un rôle pivot dans le contexte des politiques énergétiques régionales. Ces sources de financement fournissent un soutien financier crucial pour le développement et la mise en œuvre des initiatives énergétiques régionales. Le financement national garantit que les régions disposent des ressources nécessaires pour adapter les politiques énergétiques à leurs besoins et priorités spécifiques, en répondant aux défis régionaux et en exploitant efficacement les ressources énergétiques locales. D'autre part, le financement européen, souvent acheminé par des programmes tels que Horizon 2020 et les Fonds Structurels et d'Investissement Européens, favorise la collaboration et la coopération transfrontalière, permettant aux régions d'accéder à des ressources supplémentaires pour les projets d'énergie renouvelable et les améliorations du réseau. En combinant le financement national et européen, les régions peuvent accélérer la transition vers des systèmes énergétiques plus propres et plus résilients, contribuant à la fois à la durabilité locale et aux objectifs énergétiques européens plus larges.

Dans la poursuite de ces objectifs d'énergie renouvelable et de flexibilité, le rôle des politiques régionales devient particulièrement significatif. Comme la transition énergétique

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est un processus complexe, elle nécessite des stratégies personnalisées adaptées aux besoins, capacités et ressources spécifiques de différentes régions. Les politiques régionales ne fournissent pas seulement une direction pour la planification énergétique, mais créent également un environnement favorable pour attirer les investissements et favoriser les innovations technologiques [Renn et Marshall, 2016]. À cet égard, la région Occitanie en France sert de cas intrigant pour comprendre la mise en œuvre et l'impact des politiques énergétiques régionales.

### C. La région Occitanie comme cas d'étude pour la gestion régionale de la flexibilité

Située dans le sud de la France, la région Occitanie occupe une position significative dans le paysage énergétique du pays. Avec une superficie de 72 724 km<sup>2</sup> et une population d'environ 6,1 millions de personnes, l'Occitanie est la troisième région la plus peuplée de France [INSEE, 2023]. Pourtant, son importance dépasse sa taille : la région se distingue par son approche proactive de la transition énergétique et son portefeuille croissant d'énergies renouvelables. Avec une consommation régionale d'électricité équivalente à 34,8 TWh/an<sup>1</sup>, la région Occitanie représente 8,2% des 424 TWh consommés annuellement en France en 2022<sup>2</sup>. Étant une région à capacités industrielles limitées, il est compréhensible que l'Occitanie occupe seulement la 7ème position dans le classement des régions par consommation d'électricité.

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<sup>1</sup> Source : <https://www.rte-france.com/actualites/bilan-electrique-2022-occitanie>

<sup>2</sup> Source : <https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-energie-2023/16-electricite>

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Renommée pour ses conditions climatiques favorables, l'Occitanie possède d'importantes ressources solaires et éoliennes. La région abrite également plusieurs importantes centrales hydroélectriques, diversifiant davantage son mix énergétique renouvelable. En 2023, la région disposait d'une capacité photovoltaïque installée totale de plus de 2,6 GW et d'une capacité éolienne d'environ 1,7 GW, avec 5,4 GW de capacités hydroélectriques. Ces capacités renouvelables représentent 76,8% du mix de production et suffisent à couvrir 43,2% de la consommation de l'Occitanie, alors que le taux national est de 25,3%. Cela positionne l'Occitanie comme l'une des premières régions françaises en termes de production d'énergie renouvelable. Néanmoins, il faut souligner que si l'on ajoute la production de capacités solaires PV, éoliennes et hydroélectriques installées en Occitanie, elles ne couvrent que 4,5% environ de la consommation nationale. Par ailleurs, si l'on tient compte également des capacités nucléaires installées en Occitanie (2,6 GW), la région dispose d'un mix de production décarboné à 95%.

Ambitieuse dans son approche de la transition énergétique, la région Occitanie a défini plusieurs objectifs stratégiques dans son plan "Région à Énergie POSitive" (REPOS). Ce plan fixe l'objectif audacieux d'atteindre l'autosuffisance énergétique d'ici 2050, en s'appuyant uniquement sur l'énergie renouvelable produite localement. Pour réaliser cela, la région vise à réduire sa consommation d'énergie de 39 % et à multiplier par trois sa production d'énergie renouvelable d'ici 2050 [Région Occitanie, 2017].

Pour atteindre ces objectifs, l'Occitanie a mis en œuvre une gamme de politiques et d'incitations énergétiques locales. Cela inclut des soutiens financiers directs tels que la subvention des coopératives énergétiques locales, des mesures réglementaires favorisant l'efficacité énergétique et le déploiement de solutions de stockage d'énergie. De plus, la région

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a établi un système de certificats d'énergie renouvelable, qui valide l'origine de l'énergie renouvelable produite dans la région et encourage davantage d'investissements dans les projets d'énergie renouvelable.

Un aspect remarquable de la stratégie énergétique de l'Occitanie est son approche participative en matière de gouvernance énergétique. Ici, la "gouvernance" se réfère à la gestion, aux processus de prise de décision et à l'administration globale des questions liées à l'énergie au sein de la région Occitanie. Elle englobe les politiques, les réglementations et les initiatives visant à guider la transition vers des systèmes énergétiques plus propres et durables. La région encourage notamment l'implication des communautés locales dans les processus de décision énergétique, en proposant des consultations publiques et des forums où les résidents et les parties prenantes locales peuvent exprimer leurs opinions, préoccupations et suggestions liées aux politiques et projets énergétiques. Ces consultations créent une plateforme pour un dialogue ouvert et une participation active. Dans certains cas, la région collabore avec les communautés locales pour co-créeer des politiques énergétiques. Cela peut impliquer des groupes de travail conjoints ou des groupes de tâches incluant des représentants communautaires, garantissant que les politiques reflètent les besoins et les aspirations locaux. Ce fut par exemple le cas pour la conception du plan REPOS 2050 mais aussi du Pacte Vert pour l'Occitanie. Ce modèle de gouvernance inclusive, combiné à ses ressources renouvelables abondantes et à ses politiques énergétiques prospectives, fait de l'Occitanie un cas d'étude convaincant pour la gestion de la flexibilité des systèmes énergétiques régionaux. En utilisant les données disponibles de la région Occitanie, nous espérons dans cette thèse démontrer la possibilité d'une gestion régionale de la flexibilité du système énergétique, et plus largement participer au débat sur la transition énergétique afin de parvenir à une prise de décision plus éclairée.

## D. Envisager le futur à travers la prévision et la prospective

En effet, c'est le regard vers l'avenir qui détient le potentiel de véritablement orienter le cours des systèmes énergétiques régionaux. Cela est particulièrement vrai pour l'Occitanie, une région à l'aube d'une transformation énergétique significative, visant à intégrer un large éventail de ressources renouvelables. La prévision, dans le domaine des systèmes énergétiques, offre bien plus que de simples projections statistiques. Elle sert de boussole, indiquant les issues potentielles basées sur des données historiques, les tendances actuelles et une multitude de variables influentes telles que les innovations technologiques, les changements de politique et les évolutions socio-économiques. En cartographiant divers scénarios, la prévision offre un aperçu des défis et opportunités potentiels qui pourraient émerger à mesure que l'Occitanie intègre davantage l'énergie renouvelable variable dans son système énergétique.

D'autre part, l'approche prospective élargit cet horizon, adoptant une vision plus holistique. Alors que la prévision repose principalement sur une analyse quantitative, la prospective explore les dimensions qualitatives, examinant les "et si" des décisions stratégiques, des perceptions publiques et des percées technologiques. Elle favorise un dialogue entre les parties prenantes, y compris les décideurs politiques, les leaders de l'industrie et les communautés locales, créant une vision partagée du futur paysage énergétique de l'Occitanie.

En tandem, la prévision et la prospective jouent un rôle symbiotique. Tandis que la prévision jette les bases avec des prédictions basées sur les données, l'approche prospective tisse ces découvertes en un récit, intégrant des perspectives humaines, des aspirations et des



obstacles potentiels. Ensemble, ils offrent une feuille de route pour l'Occitanie, éclairant les voies pour optimiser la flexibilité du système énergétique et assurer un avenir énergétique durable et résilient.

Ainsi, cette thèse emploiera une combinaison de modèles de prévision et d'analyses prospectives, contextualisant leurs implications pour la flexibilité du système énergétique de l'Occitanie. L'objectif n'est pas seulement de prédire l'avenir, mais de le façonner activement, garantissant que la région reste à l'avant-garde de la transition énergétique mondiale.

## 3. Données et contenu de la thèse

### A. Présentation des données

Dans la recherche énergétique contemporaine, les perspectives basées sur les données sont aussi impératives qu'une théorie solide pour guider la prise de décision, le développement des politiques et les avancées technologiques. Alors que les efforts pour la transition vers des systèmes énergétiques durables s'intensifient à l'échelle mondiale, l'accès à des données énergétiques précises et complètes devient de plus en plus crucial. Reconnaisant ce besoin, plusieurs pays ont initié des plateformes de données ouvertes pour rendre les données liées à l'énergie transparentes et accessibles au public, aux chercheurs et aux décideurs. Parmi ces initiatives, la plateforme Open Data Réseaux Énergies (ODRÉ) de la France se distingue comme une ressource essentielle.

ODRÉ est une plateforme collaborative qui fournit une grande quantité de données principalement liées aux réseaux d'électricité et de gaz en France. Lancée grâce aux efforts conjoints des principaux acteurs de l'énergie, y compris Réseau de Transport d'Électricité

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(RTE), la plateforme vise à promouvoir la transparence, l'innovation et la recherche dans le secteur énergétique. Avec des ensembles de données couvrant des aspects allant de la production, la consommation et la transmission d'électricité aux profils énergétiques régionaux détaillés, ODRÉ sert de répertoire complet pour quiconque souhaite explorer les complexités du paysage énergétique français. Ainsi, pour les besoins de cette recherche doctorale, la base de données ODRÉ a été instrumentale.

Parmi l'immense quantité d'informations de la base de données ODRÉ, certains ensembles de données ont été particulièrement éclairants pour cette recherche lorsqu'ils se concentrent sur la région Occitanie : les données de consommation et de production d'électricité renouvelable, ainsi que les capacités des centrales électriques. Ces domaines spécifiques éclairent les modèles évolutifs de la demande et de l'offre d'énergie en Occitanie, offrant une compréhension globale de l'intégration des sources renouvelables dans la matrice énergétique de la région administrative.

Pour cette thèse doctorale, il a été essentiel d'examiner les données ODRÉ à diverses échelles temporelles, en se concentrant sur l'Occitanie. Qu'il s'agisse de vues d'ensemble annuelles pour des tendances régionales plus larges ou de décompositions horaires pour des analyses temporelles approfondies, la souplesse des échelles temporelles de la base de données a été inestimable. Cette approche granulaire permet une exploration complète des modèles énergétiques en Occitanie et facilite des projections et recommandations plus précises. Il est important de noter que, bien que cette introduction offre une vue d'ensemble de l'application des données, les ensembles de données spécifiques et leurs détails granulaires utilisés dans les chapitres suivants de cette thèse sont présentés méticuleusement dans chaque section respective.

D'autres sources de données incluent la littérature énergétique, notamment pour les coûts marginaux de production par technologie, mais aussi des sources plus informelles telles que

les sites web, en particulier lorsqu'il s'agit de la création de scénarios pour le futur système énergétique de l'Occitanie.

## B. Contenu de la thèse

La combinaison de la prévision et de la prospective sera au cœur de notre travail. Mais avant tout, il nous semblait essentiel de pouvoir aborder la question des besoins en flexibilité du système électrique de l'Occitanie. En d'autres termes, nous nous concentrerons d'abord sur une analyse quantitative de l'énergie qui doit être fournie ou stockée une fois toute la production des VRE injectée dans le réseau régional. Cela induira l'introduction du concept de Charge Résiduelle, un outil central pour l'équilibrage en temps réel de la charge et de l'offre. Une évaluation statistique et historique de la courbe de Charge Résiduelle du système électrique de l'Occitanie sera nécessaire, mais nous voulions aller plus loin en proposant une nouvelle méthodologie de prévision qui nous aiderait à quantifier les futurs besoins en flexibilité du système électrique de l'Occitanie. Ainsi, dans une première partie de cette thèse, notre objectif sera de prévoir les besoins réels en flexibilité du système électrique de l'Occitanie, en utilisant uniquement des données historiques. Pour cela, nous proposerons un modèle de prévision statistique de pointe qui sera utilisé avec les données de l'Occitanie pour prédire sa future courbe de Charge Résiduelle. Notre méthodologie proposée sera rigoureusement comparée à d'autres cadres statistiques pour évaluer ses performances en termes d'erreur de prédiction, et nos résultats démontreront que l'utilisation de la prévision de la Charge Résiduelle est déterminante pour les prochaines étapes de notre travail, c'est-à-dire l'optimisation du mix de flexibilité du système électrique de l'Occitanie dans diverses conditions.

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En effet, une fois les besoins en flexibilité évalués, on peut enquêter sur la manière de les satisfaire. En d'autres termes, une demande identifiée de flexibilité (incarnée par la valeur de la Charge Résiduelle à un temps  $t$ ) doit être satisfaite par une offre de flexibilité qui ne peut être fournie que par des actifs flexibles tels que des centrales électriques contrôlables ou du stockage. Ce problème d'équilibre entre l'offre et la demande de flexibilité peut être abordé comme un problème d'optimisation où la fonction objectif est de minimiser le coût de fourniture de flexibilité au système, tout en le maintenant équilibré à tout moment. Ainsi, dans un second chapitre de cette thèse, nous introduisons un cadre de gestion de la flexibilité qui vise à aborder ce problème d'optimisation. Autrement dit, nous décrivons dans ce second chapitre les mécanismes internes du modèle dit *Optimiflex* qui nous permet d'aborder la question de l'équilibre entre la demande et l'offre de flexibilité. Ce modèle d'optimisation linéaire prend comme entrées les coûts et les capacités des unités de flexibilité agrégées par technologies ainsi que la demande de flexibilité à un temps  $t$ . En résolvant la logique de l'ordre de mérite pour chaque demi-heure d'une année donnée, le modèle produit le coût total de la flexibilité ainsi que la production de flexibilité de chaque technologie. Nous testons ce cadre avec les données de l'Occitanie et résolvons le problème de gestion de la flexibilité pour l'année entière 2021, étant donné les coûts et les capacités des actifs flexibles existants en Occitanie à ce moment-là. La méthodologie proposée servira de fondement pour étudier les chemins possibles de la gestion de la flexibilité en Occitanie à l'avenir.

Dans le dernier chapitre de cette thèse, nous proposerons effectivement une analyse prospective de la gestion de la flexibilité en Occitanie. En commençant par la conception de trois scénarios pour la demande de flexibilité de l'Occitanie en 2050, nous utiliserons ensuite le modèle *Optimiflex* pour voir comment le mix de flexibilité de la région répondra à ces nouvelles exigences. De plus, nous proposerons quatre variantes du problème pour voir comment des chocs possibles sur le côté de l'offre de flexibilité pourraient affecter la gestion

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globale de la flexibilité du système électrique de l'Occitanie pour l'année 2050. Ce travail d'exploration des futurs potentiels de la gestion de la flexibilité en Occitanie fournira au lecteur des aperçus précieux sur les technologies critiques, les coûts et les recommandations politiques qui aideront à libérer le plein potentiel de l'Occitanie pour la transition énergétique.





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## 1. Decarbonizing power systems with variable and renewable energies

The 2022 6<sup>th</sup> Assessment Report (AR6) on Global Warming by the Intergovernmental Panel on Climate Change (IPCC) emphasizes the urgency of immediate and significant reductions in global greenhouse gas emissions. Their models demonstrate the profound impacts on ecosystems and human societies if the global average temperature rises beyond the 1.5°C limit set by the Paris Agreement. The impacts range from extreme weather events, rising sea levels, diminishing Arctic Sea ice, and loss of biodiversity, which are predicted to be significantly worse under a 2°C increase [IPCC, 2022]. Substantial mitigation of these consequences calls for a radical shift in our energy production and consumption patterns. The traditional fossil fuel-based energy systems contribute heavily to global carbon emissions, accounting for around 73% [IPCC, 2022] of the total greenhouse gas emissions.

Given the sizeable contribution of the energy sector to global emissions, transitioning towards cleaner, sustainable energy systems is not just an option but a necessity for human survival.

The call for a transition to clean energy is an invitation to foster investments in decarbonized energy sources such as hydropower, nuclear energy, or intermittent renewables. Indeed, the climate goals imply that countries should now replace traditional fossil-fueled energy producing technologies by more sustainable ones, i.e., technologies that emit less or no carbon dioxide during the energy production process. These technologies have different



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requirements, and their development is uneven across the globe. For instance, hydropower has been developed in western Europe since the beginning of the 20th century and now a large share of the potential for this type of energy production method has already been exploited. Nuclear power, on the other hand, is a cost and technology intensive production mean, requires very high security levels, and also depends on the stream of primary resources (especially uranium) available. Thus, this technology fosters great debates, even in countries that have adopted it early, such as France.

Finally, intermittent renewables such as solar photovoltaics and wind power are gaining momentum since the beginning of the 21st century. These technologies hold great promise due to the abundance of solar and wind resources, and also to their potential for zero-emission electricity generation. However, they also imply some debate, notably regarding the availability of rare primary resources needed to build, but also for the complex question of integrating intermittent generation in power systems that are designed historically to function with controllable generation. Still, as per the World Energy Outlook 2022 report by the International Energy Agency (IEA), solar photovoltaics (PV) and wind power constituted over 70% of the total renewable capacity additions worldwide, underscoring their pivotal role in the global energy transition [IEA, 2022].

The rapid development and deployment of these variable renewable energy sources (VRE) can be attributed to numerous factors, including advances in technology and declining costs, supportive government policies, and increasing public awareness about climate change.

First, let's dive in the intricate relationship between advances in technology and declining costs. Indeed, this interplay has transformed intermittent renewables from a niche solution to a global powerhouse in the energy sector. In particular, the costs of solar PV and wind power

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have seen a remarkable decline over the past decade. Breakthroughs in materials science and engineering have led to substantial improvements in the efficiency and performance of solar PV and wind energy systems. For solar PV, innovations in the design of solar cells and the development of new materials, such as perovskite solar cells, have significantly increased energy conversion rates [Al-Ashouri et al., 2020]. Similarly, in the case of wind power, the design of larger and more efficient turbines, including those with advanced aerodynamics and taller towers, has enabled better energy capture from the wind [Zhang et al., 2020]. In addition, technological progress has facilitated the scaling up of production for solar panels and wind turbines. With larger manufacturing volumes, the cost per unit decreases significantly. This phenomenon, known as economies of scale, has allowed for mass production of renewable energy components, making them more affordable for consumers, businesses, and utilities alike. Economies of scale were also driven by advancements in manufacturing processes and automation. Precision engineering and automated assembly lines have improved the quality and consistency of renewable energy components while minimizing labor costs. This has played a pivotal role in making renewables competitive with traditional energy sources. According to the International Renewable Energy Agency's (IRENA) Renewable Power Generation Costs in 2021, the global weighted-average cost of electricity from utility-scale solar PV fell by 85% between 2010 and 2020, making it the lowest-cost power generation technology in many parts of the world. Similarly, onshore wind costs have fallen by about 56% during the same period, while offshore wind costs have seen a 63% decrease [IRENA, 2021].

Second, combined with a growing urgency to curb greenhouse gases emissions, the implementation of supportive energy policies has played a pivotal role in driving cost savings and technological advancements in renewable energy. These policies have not only created an

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environment conducive to innovation but have also contributed to substantial reductions in the cost of clean energy technologies. For instance, consider the case of Germany's "Energiewende" policy. This forward-thinking initiative, aimed at transitioning to a low-carbon economy, introduced generous feed-in tariffs for solar power. While these incentives were initially established when solar technology costs were higher, they have been maintained to support the sector as costs decreased. This policy support has acted as a catalyst for the rapid decline in the cost of PV technology over the past decade [REN21, 2021].

Similarly, Denmark's commitment to becoming carbon-neutral by 2050 underscores the impact of policy support. The country's focus on wind power, supported by advanced turbine designs and grid integration solutions, has driven the development of more efficient wind turbines [IEA, 2019]. This policy-driven investment in offshore wind farms has been made possible by advanced technology, further illustrating the interplay between policy and innovation. It is important to note that government agencies often collaborate with industry experts to develop technology roadmaps that outline the future of renewable energy technologies. These roadmaps inform government policy and funding decisions, ensuring that support is directed toward the most promising and impactful technologies. In summary, supportive energy policies have been instrumental in driving cost savings and technological advancements in renewable energy. These policies have provided the necessary framework for innovation, enabled ambitious clean energy targets, informed regulatory frameworks, supported advocacy efforts, and laid out clear roadmaps for policy planning, which in the end has enabled learning curves to be driven towards cost decreases. The relationship between policy support and the transition to clean energy is thus crucial, as it demonstrates how favorable policies have not only followed technological advances but have actively shaped and driven them.

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Third, raising public awareness has been a vital catalyst in driving the momentum behind renewable energy adoption. Environmental concerns have been at the forefront of public awareness campaigns, such as Al Gore's "An Inconvenient Truth" documentary [Gore, 2006], shedding light on the environmental consequences of fossil fuel use, including air pollution and carbon emissions. Climate change awareness is indeed a critical aspect of this awareness, as highlighted by the IPCC, which has mobilized public opinion. The public's understanding of the role of carbon emissions in climate change has led to greater demand for renewable energy solutions that reduce carbon footprints [IPCC, 2022]. Health benefits have also been emphasized in awareness campaigns, such as the American Lung Association's "State of the Air" reports, which have drawn attention to respiratory diseases and health problems stemming from air pollution [American Lung Association, 2021]. Moreover, economic benefits associated with renewable energy have gained public attention, with the IRENA highlighting the cost-effectiveness of renewable technologies. This information has informed the public about job creation, reduced energy bills, and economic growth associated with renewable energy investments. This has translated into consumer demand, as seen in the surge in residential solar panel installations driven by homeowners seeking cost savings [Solar Energy Industries Association, 2021]. This heightened public awareness has exerted public pressure on policymakers, leading to citizen-driven advocacy and the enactment of pro-renewable energy policies. Notable examples include the Renewable Portfolio Standards (RPS) in California, influenced by public demand for cleaner energy sources [California Energy Commission, 2021]. In summary, these examples underscore the influential role of raising public awareness, connecting various aspects and contributing to the global shift toward renewable energy adoption. Heightened awareness has shaped public perceptions, influenced consumer behavior, inspired policy changes, and nurtured a shared sense of responsibility for transitioning to a cleaner and more sustainable energy future.

## 2. Research question: The issue of power system flexibility

Despite these positive trends, integrating high shares of VRE into the power system presents notable challenges due to their inherent variability and uncertainty. Indeed, electricity is often comprised as a non-storable good, which translates into an equilibrium constraint between supply and demand at any time. This constant equilibrium constraint has been formulated under the Kirchoff's laws, which generalize the idea of conservation of load within any given power system.

Meanwhile, the intermittency of sunlight and wind implies that solar PV and wind power production fluctuates over different timescales –from instantaneous changes to middle-long term variations, i.e., seconds to seasons. Such fluctuations introduce additional constraints on the initial load balancing constraint, thereby requiring effective measures to balance supply and demand. If the initial constraint of load balancing has been well studied in the academic literature, the rise of VRE implies new constraints due to their inherent variability and intermittency, which will be our focus in this thesis.

To be more precise, the sensitivity to initial conditions problem, which states that small variations in the starting conditions of a complex system can lead to significantly different outcomes or trajectories over time makes the exercise of predicting the weather with a perfect accuracy an unachievable task. VRE's output, which relies on weather conditions, is therefore deemed as hard-to-predict. This dependance to weather conditions also signifies that VRE's output is not controllable which introduces a totally new paradigm for electricity generation that used to rely on controllable production means such as coal or gas-fired power plants. VRE can thus be the source of technical issues on the power system, as well as high volatility on power markets [Nicolosi, 2010 ; Hirth, 2013 ; Benhmad and Percebois,

2018a,b]. Therefore, many researchers and stakeholders state that power systems incorporating more and more VRE must also be more and more *flexible* [Holtinen et al., 2013 ; Oleinikova and Obushevs, 2015 ; Kondziella and Bruckner, 2016 ; Richard Druce et al., 2016].

## A. Defining flexibility

Flexibility is a *portmanteau* word which encompasses many different ideas related to matching load and electricity generation at any time. A general definition of a power system flexibility is its “*ability to cope with changes either in electricity generation or consumption*” [Hubert et al., 2014]. In this view, power system flexibility is the inherent and dynamic capability of an electrical grid to promptly, seamlessly, and efficiently adapt to the continuous fluctuations in both electricity generation and consumption. It is inherent and dynamic in the sense that flexibility is not an external feature that can be added or removed at will. It is an intrinsic characteristic deeply embedded within the grid's infrastructure and operational framework. This capability is not static but continually evolves and adapts to changing conditions and requirements. Thus, flexibility demands a swift response to changes in generation and consumption, which means that grid operators must be capable of making real-time adjustments to balance supply and demand, minimizing disruptions, and maintaining grid stability. However, flexibility extends beyond mere response to encompass efficiency. The grid must adapt in a manner that minimizes energy losses and maximizes the efficient utilization of renewable and non-renewable resources. Overall, the ultimate goal of power system flexibility is to ensure that electricity is consistently and reliably delivered to end-users without interruptions or disruptions, at the lowest cost.

As a matter of fact, the concept of flexibility implies various temporal aspects, each of one being related to a concrete issue. From real-time to short term (i.e., minutes to hours),

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flexibility is required mostly for grid balancing [Lannoye et al., 2012]. From day-ahead to week-ahead (i.e., mid-term), flexibility will refer to the producers and market participants' ability to adapt either optimal generation units scheduling or electricity pricing to forecasted load and generation variations [Shaaban et al., 2018 ; de Lagard and Lantz, 2018]. Finally, on longer timescales like months or years, matching electricity demand and production will require production units scheduling, building new plants or storage capacities, specific energy policy design as well as grid investments to follow long-term load trends or seasonal variations. This idea can be referred to as long-term flexibility [Esteban et al., 2012 ; Steinke et al., 2013 ; Ma et al., 2013 ; Heleno et al., 2015 ; Holttinen et al., 2016].

To better illustrate what flexibility refers to, it can be useful to look at existing and future mechanisms designed to ensure a constant matching of electricity production and demand. Lund et al (2015). review the flexibility measures that would enable large shares of VREs to be added to power systems. As there are numerous measures identified, they propose a classification that ranges from Demand Response measures to Electricity Markets measures. To simplify the categorization and better represent the action scope of flexibility solutions, we propose to classify existing and developing them in three main categories, which are simply:

- technology-related solutions,
- grid-related solutions
- market-related solutions.

Most of **technological flexibility solutions** like spinning reserves or controllable generation units (e.g., fossil-fueled plants) are already in use today, as the load balancing constraint is a historical feature of all power systems.[Ortega-Vasquez and Kirschen, 2007 ; Jenkins et al., 2018]. In response to the new constraints introduced by VRE, new types of

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technological flexibility solutions are also emerging. For instance large-scale electricity storage technologies (e.g., Pumped Hydro Storage (PHS), flywheels, supercapacitors, stationary batteries, or Power-to-X) are also part of technological flexibility options, yet the majority of them is still in early development [Denholm and Hand, 2011 ; Schill, 2014 ; Fuel Cell and Hydrogen Joint Undertaking (FCHJU),2015, Blanco and Faaij, 2018 ; Percebois and Pommeret, 2019]. Last, some technological flexibility options are linked to VRE technologies themselves. VRE generation can indeed be curtailed by rotating the blades of wind turbines for instance, [Bongers et al., 2019]. Geographical spreading of VRE capacities can also be classified as a technology-related flexibility solution, as they can be distributed across large territories to benefit from different local weather conditions [Sarafidis et al., 1999 ; Krakowski et al., 2016]. Finally, technologies that enable a better forecasting of VRE's output can also be added to the technology-related flexibility solutions category, as these techniques are critical to assess the flexibility requirements of a given power system.

The second category relates to **grid developments**, either at the transmission or distribution level, that can be implemented to avoid congestions (e.g., grid capacity extensions) or to benefit from different local weather conditions (e.g., interconnections) [Vito et al., 2017 ; Karimi-Arpanahi et al., 2020]. It is worth mentioning that grids can adopt various shapes, from traditional national grids in which the transmission lines are vital to transport electricity over long distances, to micro-grid that enable local energy communities, peer-to-peer trading, and fine adjustments of load and generation to drive flexibility. The arrangement of lower scale grids and their relationship to the centralized supranational grid are complex and intricate, as the decentralization of decisions to lower grid levels can impact the functioning of the whole system.



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Finally, within the **market solutions** category, we include all market mechanisms allowing a faster and more adaptive matching between load and generation (e.g., intra-day contracts on wholesale market, capacity market) and a better demand-side management (e.g., demand-response market) [Sharifi et al., 2017 ; Villar et al., 2018]. Note that this kind of flexibility solutions is most often relying on specific technology, either communication in the case of intra-day contracts or generation technologies when it comes to the capacity market. The institutional form of a market is however the common denominator for these flexibility solutions.

In Table 1 we propose to present the different flexibility solutions, their activation time, the timescale over they can be used and their current maturity. The table make use of the classification described above and include sub-categories for the technology-related solutions, as they are numerous and different in nature. As presented in the table, technology-related solutions are most often use for short-term balancing as their activation time is usually very fast. Oppositely, long-term flexibility requirements are most addressed by large-scale investments, such as grid interconnections. This table represents a panorama of flexibility options and their main characteristics at the present moment and will be subject to new entries as flexibility becomes a key issue for power system integrating large shares of VRE.

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Flexibility options	Activation time	Offered flexibility timescale	Maturity
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**Technology related**Stability reserves

Primary reserve	< 30 seconds	Very short-term	In use
Secondary reserve	Between 30 seconds and 15 minutes	Very short-term	In use
Tertiary reserve	From 13 minutes up to 2 hours	Short-term	In use

Controllable production units

Hydropower	Within a few minutes	Short, mid and long term	In use
Nuclear power	1-5% capacity/min ramp rate	Short, mid and long term	In use
OCGT	20% capacity /min ramp rate	Short and mid-term	In use
CCGT	5-10% capacity /min ramp rate	Short and mid-term	In use
Coal plant	1-5% capacity /min ramp rate	Short and mid-term	In use
Combustion turbines	1-5% capacity /min ramp rate	Short and mid-term	In use
Biofueled plants	1-5% capacity /min ramp rate	Short and mid-term	Developing

VRE related

Curtailment	Within a few minutes	Short-term	In use
Geographical spreading	Months	Long-term	In use and developing
Enhanced output forecasting	Between a few minutes and a few hours	Very short to long-term	In use and developing

Storage

Flywheels	Within a minute	Very short to short-term	Developing
Stationary batteries	Within a minute	Very short to short-term	Very early development
Supercapacitors	Within a minute	Very short to short-term	Very early development
Vehicle-to-Grid	Between a few minutes and a few hours	Very short to short-term	Very early development
Pumped Hydro Storage	Within a few minutes	Short, mid and long-term	In use
Pumped Heat Electricity Storage	Within a few minutes	Short-term	Developing
Compressed Air Electricity Storage	Within a few minutes	Short to mid-term	Early development
Power-to-X	Within a minute	Short, mid and long-term	Very early development
Concentrated solar	Within a minute	Short-term	Early development

**Market related**

Demand-response	Within a few minutes	Very short to short-term	In use
Capacity market	Within a few minutes	Short-term to long-term	In use
Intra-day contracts	Within an hour	Short-term	In use
Energy Efficiency Certificates	Months	Long-term	In use

**Grid related**

Capacity extensions	Months to years	Long-term	In use
Interconnections	Years	Very long-term	In use and developing

Table 1 : Classification of existing and future flexibility solutions

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Achieving high levels of flexibility is not without challenges. A primary obstacle is the fact that most power systems around the world have been designed and operated based on predictable and controllable dispatchable resources, primarily fossil fuel-based power plants. With the recent increase of fossil fuels prices (especially natural gas), this paradigm could rapidly evolve towards the primary use of renewable sources to ensure base generation. However, integrating a large amount of VRE introduces new dimensions of variability and uncertainty, which traditional power systems may not be well-equipped to handle. This calls a significant transformation in the way power systems are designed, operated, and regulated. Indeed, the rise of VRE capacities involves a movement from traditional grids organized around centralized generation and decision-making to a more decentralized way of operating the power system. As VRE generation is spread across the territory, this new kind of decentralized generation requires a more granular approach when it comes to manage the electricity flows along the grid.

One potential approach to manage this transition is to adopt a regional perspective on power system flexibility. Regional power systems can be a way to represent parts of the national power system based on an administrative division of the territory. This approach is therefore a new way of looking at certain regions of the national power system and can be both motivated by and a tool to implement local energy policies. Indeed, this regional representation, could potentially offer better opportunities for harnessing local flexibility resources, such as distributed energy storage and demand response. However, transitioning from a national to a regional representation of the power system involves a shift in the balance of power and responsibility between different stakeholders, and raises questions around issues of power system security, reliability, and fairness.

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This introduces a new set of challenges and complexities, and hence, forms the crux of our research question: **What would a regional management of power system flexibility look like?** In order to answer this, it is necessary to delve into the functioning of national power systems, and the potential role and impact of regional power systems within them.

### B. A new approach to achieve VRE integration with the idea of regional power system

The conventional power system relies on centralized generation in large power plants, with power transmission over long distances to the load centers. This historical centralized way of functioning is due to several arguments derived from economic theory. One of the fundamental principles motivating this approach is the concept of economies of scale. This principle suggests that as the scale of production increases, the average cost per unit of output decreases. As a result, the marginal cost of one additional unit of energy demand becomes null. In the context of electricity generation, centralized power plants, often fueled by coal, natural gas, or nuclear sources, are typically large and benefit from economies of scale. These large plants can generate electricity at a lower cost per unit than smaller, decentralized generators. This economic advantage has historically made centralized power generation more cost-effective. Moreover, the capital-intensive nature of conventional power generation technologies, such as coal or nuclear power plants, makes it more feasible for a limited number of large entities, such as utilities or power companies, to invest in and operate these facilities. The high upfront capital costs and long payback periods are better suited to centralized ownership, where organizations can spread these costs over time. Additionally, economic theory also acknowledges the role of regulation and government intervention in

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shaping industry structures. Historically, regulatory frameworks often favored centralized utilities due to the perceived economies of scale and the need for infrastructure investments. This regulatory environment encouraged the development of large, centralized power plants and grid systems. Lastly, centralized power generation facilities are well-suited for integration into centralized electrical grids, which cost structure implies a natural monopoly position. This allows for efficient transmission and distribution of electricity over long distances to meet the needs of a large population or region. Centralized grids can optimize the allocation of electricity from various sources, including power plants, to consumers, reducing transmission losses and improving overall grid reliability. However, the advent of VRE has added a decentralized feature to power generation. This decentralized nature of power generation poses challenges to the conventional grid, including maintaining system stability and ensuring power quality.

In response to these challenges, the concept of regional power systems is garnering attention. Unlike the conventional national power system, a regional power system representation can enable a more agile and responsive decision-making in accommodating the variability of localized VRE generation. Regional power systems can enable more localized decision-making and management of resources, which could potentially unlock unique opportunities for enhancing power system flexibility. For instance, distributed energy resources like small-scale storage, demand response, and local renewable generation could be managed more effectively at a regional scale [Hoppmann et al., 2014]. As VRE increase their share in the energy mix, the interconnections and coordination between national and regional power systems become even more significant, and understanding their mutual dependencies is vital for reliable and efficient system operation [Hirth and Ziegenhagen, 2015].

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Decentralized regional power systems, while offering various advantages, also come with drawbacks. Managing a decentralized grid with a diverse mix of distributed energy sources can be complex. It often requires sophisticated control and communication systems to ensure smooth operations, monitor energy flows, and respond to grid disturbances. Moreover, integrating decentralized systems into a larger regional or national grid can be technically challenging. Ensuring compatibility and stability when connecting various distributed resources may require additional investments, and existing regulations and policies designed for centralized grids may not be well-suited to decentralized systems. Adapting regulatory frameworks to accommodate decentralized energy generation and distribution can be also a lengthy and complex process. Finally, coordinating maintenance and repairs across a decentralized grid with a multitude of distributed assets can be logistically demanding. Ensuring the reliability and safety of these systems requires effective maintenance procedures and skilled personnel.

Therefore, the development and operation of regional power systems within national power systems necessitate a careful consideration of their technical, economic, and institutional interdependencies. Technically, the interconnected nature of power systems implies that the operations of a regional power system can have effects on the larger national power system, and vice versa. Indeed, since regional power systems are interconnected, a fault or outage in one part of the system can quickly propagate, potentially causing extensive blackouts across the entire system. Moreover, these sub-systems may lead to a single point of failure, making them vulnerable to natural disasters, cyberattacks, or equipment failures that can have catastrophic consequences. Economically, the costs and benefits associated with regional flexibility resources need to be evaluated within the broader context of national power system operation. The economic implications of this point of view shift are multifaceted. On one hand, localized generation can reduce transmission losses and improve

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grid efficiency, leading to potential cost savings. It can also enhance energy security by reducing dependence on long-distance transmission lines. On the other hand, the upfront costs of distributed resources and the need for grid upgrades to accommodate variable generation can increase overall costs. In addition, urban areas, for instance, often have higher electricity demand due to denser populations and industrial activity, while rural regions may have lower consumption levels. Due to the French energy policy guideline of tariff equalization, it is worth noting that denser populations areas subsidize the development of the electrical grid in rural areas. In a centralized power system, electricity can be efficiently generated in large power plants and transmitted over long distances to meet these varying demands. Comparatively, costs of upgrading the regional grid to satisfy these varying needs can be higher. Institutionally, new forms of governance and regulatory frameworks may be required to enable the integration and operation of regional power systems [Roelich et al., 2015].

Such considerations guide us towards the understanding of regional energy policies. These energy policies refer to the specific set of rules, regulations, and strategies designed at the regional level to guide the production, distribution, and consumption of energy. Regional energy policies come up with several advantages, making them interesting to study in the context of power system flexibility. First, regional energy policies can be finely tuned to address the unique characteristics and challenges of a particular area. This granularity allows policymakers to design flexibility solutions that are specifically suited to the local energy landscape, accounting for factors such as renewable resource availability, infrastructure constraints, and regional demand patterns. Moreover, by focusing on regional energy policies, decision-makers can optimize the utilization of local energy resources. For example, regions with abundant solar potential can emphasize solar power generation and integration into their flexibility strategies, while regions with strong wind resources can prioritize wind energy

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solutions. In other cases, regions with geothermal resources can develop this form of energy harvesting, while regions that do not possess significant renewable sources can adapt their grid infrastructure to benefit from neighboring regions with higher potentials. This resource-centric approach enhances the overall efficiency and sustainability of the energy system. In addition, regional policies can facilitate the alignment of energy infrastructure with flexibility needs. This includes planning and investments in grid enhancements, energy storage facilities, and demand-side management programs tailored to the specific requirements of the region. Such alignment ensures that infrastructure developments are synchronized with regional energy goals. Besides this, regional energy policies can stimulate local economic development by promoting the growth of energy-related industries and job creation. For instance, regions can incentivize the development of renewable energy projects, attracting investment and creating employment opportunities. Finally, different regions may have varying environmental priorities and concerns. Regional policies can take into account these environmental factors, ensuring that flexibility solutions minimize negative impacts on local ecosystems while maximizing clean energy integration [Kern and Bulkeley, 2009]. .

A prominent example of a regional energy policy is found in the State of California, USA. Recognizing the significant potential of renewable energy in the state, California has implemented an ambitious RPS that requires utilities to obtain 60% of their power from renewable sources by 2030 and aims for a completely carbon-free electricity sector by 2045 [California Energy Commission, 2021]. This policy has been a significant driver of the state's renewable energy growth, which stood at 49% of total electricity generation in 2022, much higher than the national average of 20% (U.S. Energy Information Administration (EIA), 2023). To address the issue of power system flexibility, California has introduced specific mandates and incentives to promote energy storage technologies, which play a critical role in



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enhancing power system flexibility. The state's storage targets require utilities to procure a certain amount of energy storage capacity, helping to smooth out fluctuations in renewable energy generation and support grid stability. In addition, California has also prioritized demand response programs as part of its flexibility strategy. These programs enable consumers to adjust their electricity usage during peak demand periods or in response to grid needs, reducing the strain on the system and enhancing its flexibility. On the front of grid adaptation, California has invested in grid modernization initiatives. These efforts include upgrading grid infrastructure, implementing advanced grid management technologies, and enhancing grid resilience to better handle variable generation.

Another example of a regional energy policy stands in the way the Provence-Alpes-Côte d'Azur region of southern France accommodates the increase of solar PV capacities within its territory. While PV contributes to only about 10% of renewable electricity production in France, there are ambitious targets to increase PV capacity by five times by 2028 and ten times by 2030 in the Provence-Alpes-Côte d'Azur region. However, this growth should not harm agricultural or natural areas. To guide PV project development, a regional framework has been established, emphasizing PV on rooftops, and parking shelters and providing guidance for PV ground installations. For PV ground projects, a sensitivity assessment grid prioritizes areas for development, considering prohibitive zones, high-stakes zones, moderate-stakes zones, and preferred zones based on various factors. This provides an example of how regional energy policies can take into account environmental factors in the pursuit of a broader energy transition [DREAL PACA, 2019].

While the topic is gaining momentum, it is worth noting that regional energy policies are an emergent tool that accompany national initiatives for the energy transition. Indeed, it is the very development of VREs that renders the regional approach worthwhile because of their

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decentralized nature, and this development is recent in most of power systems. Therefore, it is understandable that only a few relevant examples of successful regional energy policies can be found. This is due to several factors, the primary one being that regional power systems are representations of parts of a broader national or supranational power system. This kind of representation is based on an administrative cutting of the national territory, which can be different among countries. For instance, a region in France does not mean the same as a state in the USA, or a Lander in Germany, as they do not have the same political and administrative powers and responsibilities. Another reason is that unlike national energy policies, which are often published on government official documents, regional policies may not be accompanied with enough sources for information, for instance relative to the methodology used for their studies, like it is the case for the REPOS 2050 scenario. It is even worse for data about regional power systems or energy policies, which is not readily available or centralized. Even when information is available, it may be fragmented across multiple sources, including regional government websites, research institutions, and reports, making it time-consuming to compile a comprehensive overview. Finally, the diversity of tools used in regional energy policies can make them difficult to analyze in a comparative way. Indeed, regional energy policies can adopt several mechanisms to promote renewable energy and power system flexibility. These may include direct financial incentives (such as feed-in tariffs, tax credits), regulatory measures (such as renewable portfolio standards, net metering), and market-based mechanisms (such as renewable energy certificate systems, carbon pricing). The choice of policy mechanisms depends on various factors, including the local renewable energy resource availability, existing energy infrastructure, and local market conditions [Couture et al., 2010].

It is worth noting that National and European financing plays a pivotal role in the context of regional energy policies. These sources of funding provide crucial financial support for the

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development and implementation of regional energy initiatives. National funding ensures that regions have the resources to tailor energy policies to their specific needs and priorities, addressing regional challenges and harnessing local energy resources effectively. On the other hand, European financing, often channeled through programs such as Horizon 2020 and the European Structural and Investment Funds, fosters collaboration and cross-border cooperation, enabling regions to access additional resources for renewable energy projects and grid enhancements. By combining national and European funding, regions can accelerate the transition to cleaner, more resilient energy systems, contributing to both local sustainability and broader European energy objectives.

In the pursuit of these renewable energy and flexibility goals, the role of regional policies becomes particularly significant. As energy transition is a complex process, it necessitates customized strategies tailored to the specific needs, capacities, and resources of different regions. Regional policies not only provide direction for energy planning but also create a favorable environment to attract investments and foster technological innovations [Ortwin Rennand J. Marshall, 2016]. In this regard, the Occitanie region in France serves as an intriguing case for understanding the implementation and impact of regional energy policies.

### C. French region Occitanie as a case study for regional flexibility management

Situated in the southern part of France, the Occitanie region holds a significant position in the country's energy landscape. With a surface area of 72,724 km<sup>2</sup> and a population of approximately 6.1million people, Occitanie is the third most populated region of France [INSEE, 2023]. Yet, its significance extends beyond its sheer size: the region stands out for its

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proactive approach to energy transition and its growing renewable energy portfolio. With a regional electricity consumption equal to 34.8 TWh/year<sup>3</sup>, the Occitanie region represents 8.2% of the 424 TWh consumed yearly in France in 2022<sup>4</sup>. Being a region with only limited industrial capacities, it is understandable that Occitanie holds only the 7<sup>th</sup> position in the ranking of regions per electricity consumption.

Renowned for its favorable climatic conditions, Occitanie boasts substantial solar and wind resources. The region also houses several significant hydroelectric power plants, further diversifying its renewable energy mix. By 2023, the region had a total installed photovoltaic capacity of over 2.6 GW and wind power capacity of approximately 1.7 GW, with 5.4 GW of hydroelectric capacities. These renewable capacities represent 76.8% of the generation mix and are enough to cover 43.2% of the Occitanie consumption, while the national rate is 25.3%. This positions Occitanie as one of the top French regions in terms of renewable energy production. Still, we must underline the fact that if we add the production of solar PV, wind and hydroelectric capacities installed in Occitanie, they only cover around 4.5% of the national consumption. In addition, if we also account for the nuclear capacities installed in Occitanie (2.6 GW), the region has a generation mix that is 95% decarbonated.

Ambitious in its approach to energy transition, the Occitanie region has outlined several strategic objectives in its "Région à Energie POSitive" (REPOS) plan. This plan sets the audacious goal of achieving energy self-sufficiency by 2050, solely relying on locally produced renewable energy. To actualize this, the region aims to reduce its energy consumption by 39% and multiply by three its renewable energy production by 2050 [Région Occitanie, 2017]. To accomplish these objectives, Occitanie has implemented a range of local energy policies and incentives. These include direct financial supports like the subvention of

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<sup>3</sup> Available at: <https://www.rte-france.com/actualites/bilan-electrique-2022-occitanie>

<sup>4</sup> Available at: <https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-energie-2023/16-electricite>

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local energy cooperatives, regulatory measures promoting energy efficiency, and the deployment of energy storage solutions. Moreover, the region has established a renewable energy certificate system, which validates the origin of renewable energy produced in the region and encourages further investment in renewable energy projects.

One notable feature of Occitanie energy strategy is its participatory approach to energy governance. Here, "governance" refers to the management, decision-making processes, and overall administration of energy-related matters within the region of Occitanie. It encompasses policies, regulations, and initiatives aimed at guiding the transition to cleaner and more sustainable energy systems. The region notably encourages the involvement of local communities in energy decision-making processes, by proposing public consultations and forums where residents and local stakeholders can express their opinions, concerns, and suggestions related to energy policies and projects. These consultations create a platform for open dialogue and active participation. In some cases, the region collaborates with local communities in co-creating energy policies. This can involve joint working groups or task forces that include community representatives, ensuring that policies reflect local needs and aspirations. This has been for example the case for designing the REPOS 2050 plan but also the Green Pact for Occitanie. This inclusive governance model, combined with its abundant renewable resources and forward-looking energy policies, makes Occitanie a compelling case study for regional power system flexibility management. By making use of available data from the Occitanie region, we expect in this thesis to demonstrate the possibility of a regional management of power system flexibility, and more broadly to participate to the debate around the energy transition in order to achieve more informed decision-making.

## D. Envisaging the future through forecasting and prospective

Indeed, it is the gaze towards the future that holds the potential to truly steer the course of regional power systems. This is especially true for Occitanie, a region standing at the cusp of a significant energy transformation, aiming to integrate an expansive suite of renewable resources.

Forecasting, in the realm of energy systems, provides more than just statistical projections. It serves as a compass, pointing towards potential outcomes based on historical data, current trends, and a plethora of influencing variables such as technological innovations, policy shifts, and socio-economic changes. By mapping out various scenarios, forecasting offers a glimpse into potential challenges and opportunities that might emerge as Occitanie further embeds variable renewable energy into its power system.

On the other hand, the prospective approach broadens this horizon, embracing a more holistic view. While forecasting primarily leans on quantitative analysis, prospective dives into the qualitative dimensions, exploring the "what-ifs" of strategic decisions, public perceptions, and technological breakthroughs. It fosters a dialogue between stakeholders, including policymakers, industry leaders, and local communities, creating a shared vision of the future energy landscape of Occitanie.

In tandem, forecasting and prospective play a symbiotic role. While forecasting lays the groundwork with data-driven predictions, the prospective approach weaves these findings into a narrative, integrating human insights, aspirations, and potential roadblocks. Together, they provide a roadmap for Occitanie, illuminating pathways for optimizing power system flexibility and ensuring a sustainable, resilient energy future.

Thus, this thesis will employ a combination of forecasting models and prospective analyses, contextualizing their implications for Occitanie's power system flexibility. The endeavor is not just to predict the future but to actively shape it, ensuring that the region remains at the forefront of the global energy transition.

## 3. Data and outline of the thesis

### A. Presentation of the data

In contemporary energy research, data-driven insights areas imperative as sound theory to guide decision-making, policy development, and technological advancements. As efforts intensify globally to transition towards sustainable energy systems, access to accurate and comprehensive energy data becomes ever more crucial. Recognizing this need, several countries have initiated open data platforms to make energy-related data transparent and accessible to the public, researchers, and policymakers. Among these initiatives, France's Open Data Réseaux Énergies (ODRÉ) stands out as a pivotal resource.

ODRÉ, a collaborative platform, provides a wealth of data primarily related to the electricity and gas networks in France. Launched with the joint efforts of major energy stakeholders, including the Réseau de Transport d'Électricité (RTE), the platform aims to promote transparency, innovation, and research in the energy sector. With datasets encompassing aspects from electricity production, consumption, and transmission to detailed regional energy profiles, ODRÉ serves as a comprehensive repository for anyone keen to

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delve into the intricacies of France's energy landscape. Thus, for the purposes of this doctoral research, the ODRÉ database has been instrumental.

Within the vast troves of information in the ODRÉ database, certain datasets have been particularly enlightening for this research when focused on the Occitanie region: consumption and renewable electricity production data, and power plant capacities data. These specific areas shed light on the evolving patterns of energy demand and supply in Occitanie, offering a holistic understanding of how renewable sources are being integrated into the administrative region energy matrix.

For the purpose of this doctoral thesis, it has been essential to examine the ODRÉ data across various timescales, focusing on Occitanie. Whether it's yearly overviews for broader regional trends or hourly breakdowns for in-depth temporal analyses, the flexibility of the database's temporal scales has been invaluable. This granular approach allows for a comprehensive exploration of energy patterns within Occitanie and facilitates more accurate projections and recommendations. It is worth noting that while this introduction provides an overarching view of the data's application, specific datasets and their granular details utilized in the subsequent chapters of this thesis are presented meticulously within each respective section.

Other sources of data include the energy literature notably for marginal costs of production per technology, but also more informal sources such as websites, especially when coming to the creation of scenarios for the future Occitanie power system.



## B. Content of the thesis

Combining forecasting and prospective will be at the heart of our work. But before anything else, it seemed compulsory to us that we would need to be able to address the question of the flexibility requirements of Occitanie power system. In other terms, we will focus first on a quantitative analysis of the energy that must be supplied or stored once all VRE production has been injected into the regional grid. This will induce the introduction of the Residual Load concept, a central tool when it comes to real-time load and supply balancing. A statistical and historical assessment of the Residual Load curve of Occitanie power system will be needed but we wanted to go a step further by proposing a new forecasting methodology that would help us to quantify the future Occitanie power system flexibility requirements. Therefore, in a first part of this thesis, our aim will be to forecast the actual flexibility requirements of Occitanie power system, using only historical data. To perform this, we will propose a state-of-the-art statistical forecasting model that will be used with Occitanie data to predict its future residual load curve. Our proposed methodology will be rigorously compared with other statistical frameworks to assess its performance in terms of prediction error, and our results will demonstrate that the use of Residual Load forecasting is determinant for the next steps of our work i.e., optimizing the flexibility mix of Occitanie power system under various conditions.

Indeed, once flexibility requirements have been assessed, one can investigate the way to address them. In other terms, an identified demand for flexibility (embodied has the value of the residual load at time  $t$ ) must be met by a supply of flexibility which can only be delivered by flexible assets such as controllable power plants or storage. This problem of flexibility supply and demand balancing can be approached as an optimization problem where the

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objective function is to minimize the cost of providing flexibility to the system, while keeping it balanced at any time. Thus, in a second chapter of this thesis, we introduce a flexibility management framework that aims to address this optimization problem. Said otherworldly, we describe in this second chapter the inner mechanics of the so-called *Optimiflex* model that enables us to address the question of flexibility demand and supply matching. This linear optimization model takes as inputs the costs and capacities of flexibility units aggregated by technologies as well as the demand for flexibility at time  $t$ . Solving the merit-order logic for each half-hour of a given year, the model outputs the total cost of flexibility as well as the flexibility production of each technology. We test this framework with Occitanie data and solve the flexibility management problem for the full year of 2021, given the cost and capacities of existing flexible assets in Occitanie at that time. The proposed methodology will serve as a foundation for studying the possible paths flexibility management could occur in Occitanie in the future.

In a final chapter of this thesis, we will indeed propose a prospective analysis of flexibility management in Occitanie. Starting with the conception of three scenarios for the flexibility demand of Occitanie in 2050, we will then make use of the *Optimiflex* model to see how the flexibility mix of the region will respond to these new requirements. Additionally, we will propose four variations of the problem to see how possible shocks on the flexibility supply side could affect the overall flexibility management of Occitanie power system for the year 2050. This work of exploring the potential futures of Occitanie flexibility management will provide the reader with some worthwhile insights about critical technologies, costs and policy recommendations that will help unlock the full potential of Occitanie for the energy transition.



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# CHAPTER I

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Forecasting power system flexibility requirements

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A hybrid deep-learning approach

*Théotime Coudray*



# SYNTHESE DU CHAPITRE 1

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## 1. Introduction

Le premier chapitre de cette thèse se penche sur la question de la modélisation et de la prévision des besoins de flexibilité d'un système électrique donné. Pour ce faire, est introduite la notion de Charge Résiduelle (RL), qui correspond à la quantité d'énergie qu'il reste à fournir pour couvrir la demande lorsque l'ensemble de la production intermittente a été injectée dans le réseau. En d'autres termes il s'agit de savoir ce qu'il reste à produire ou à stocker, selon le signe de la fonction RL, pour équilibrer la demande une fois la production VRE comptabilisée. L'équation de la fonction RL est donc simplement :

$$RL = \text{Consommation} - (\text{Production PV} + \text{Production éolienne})$$

Cette représentation mathématique des besoins de flexibilité d'un système électrique est utile car elle permet de se pencher sur les divers aspects temporels de la notion de flexibilité. En effet, en utilisant des séries temporelles de RL, avec un pas de temps suffisamment court, nous pouvons observer à la fois les fluctuations de court terme de la production VRE et les variations de plus long terme des motifs de consommation. La fonction de RL devient alors un outil précieux car elle incarnera, tout au long de cette thèse, l'équivalent d'une *Demande de flexibilité*. L'objectif affiché de ce chapitre est de pouvoir prévoir cette demande de flexibilité.

## 2. Méthodologie

Une fois ce cadrage théorique déployé, le chapitre décrit en détail deux approches complémentaires utilisées pour la prévision de la courbe de charge résiduelle d'un système électrique. La première approche, la Décomposition Empirique en Modes (EMD) et ses extensions, est une méthode de traitement de signal qui décompose une série temporelle complexe en fonctions de mode intrinsèques (IMF) et un résidu. Cette décomposition permet de mieux analyser ou prédire des séries temporelles non-linéaires et non-stationnaires en isolant les motifs oscillatoires. La méthode EMD a été affinée pour résoudre le problème de mélange des modes par la création de variantes telles que la Décomposition Empirique en Modes d'Ensemble (EEMD) et la Décomposition Empirique en Modes d'Ensemble Complète avec Bruit Adaptatif (CEEMDAN).

La seconde approche implique l'utilisation de Réseaux de Neurones Artificiels (ANN) et leurs variantes spécifiques aux données temporelles, notamment les Réseaux Neuronaux Récurrents (RNN) et les unités de Mémoire à Long Terme-Court Terme (LSTM). Les LSTM, en particulier, sont adaptés pour capter des dépendances à court et à long terme dans des séries temporelles, en surmontant les limitations des RNN traditionnels. Une avancée récente dans ce domaine est la combinaison des LSTM avec des Réseaux de Neurones à Convolution pour former des ConvLSTM-2D, capables de traiter des séries temporelles complexes en apprenant à la fois les motifs spatiaux et temporels.

Dans la méthodologie proposée, l'étude utilise d'abord CEEMDAN pour transformer la courbe de charge résiduelle en un ensemble de IMFs, facilitant ainsi la prévision grâce à leurs propriétés stationnaires. Ces IMFs sont ensuite utilisées comme entrées dans un modèle ConvLSTM multivarié pour réaliser des prévisions de séquences quotidiennes. Le processus de prévision adopte une validation par marche en avant, intégrant des données réelles dans l'historique pour améliorer la précision des prévisions futures. Ce cycle itératif de formation et d'ajustement des prévisions en fonction des données actuelles vise à produire des résultats précis et fiables pour la prévision du besoin en flexibilité des systèmes électriques.

### 3. Application à la région Occitanie

Dans le but de proposer une comparaison de la méthodologie proposée avec des données véritables issues de l'ODRE, on évalue différents modèles de prévision de la RL de la région française d'Occitanie, en utilisant deux métriques, l'Erreur Moyenne Absolue en Pourcentage (MAPE) et l'Erreur Quadratique Moyenne (RMSE). Quatre modèles ont été comparés : ARIMA, LSTM, CEEMDAN-LSTM et CEEMDAN-ConvLSTM-2D. Le modèle CEEMDAN-ConvLSTM-2D a démontré une performance supérieure, avec un MAPE de 3,79% pour les premières 24 heures et de 3,02% pour la période complète de prévision de 8 736 heures. Ses valeurs de RMSE étaient de 260,33 MW pour les premières 24 heures et de 137,12 MW pour la période complète. Les modèles ARIMA, LSTM et CEEMDAN-LSTM ont montré des taux d'erreur plus élevés tant pour le MAPE que pour le RMSE, indiquant une précision de prévision inférieure par rapport au modèle CEEMDAN-ConvLSTM-2D. Grâce à cette application, le chapitre conclut que le modèle CEEMDAN-ConvLSTM-2D offre une



meilleure précision de prévision tant pour les horizons à court terme (premières 24 heures) que pour les horizons à long terme (année complète).

## 4. Discussion et conclusion

En fin de chapitre est également examiné comment l'augmentation des capacités des VRE pourrait affecter la variabilité de la RL en Occitanie. Utilisant l'indice de Sobol, un outil dans l'analyse de sensibilité basée sur la variance, le chapitre quantifie l'impact de la variance de chaque variable d'entrée (consommation d'électricité, production éolienne et photovoltaïque solaire) sur la variance de la RL horaire en Occitanie.

Les indices de Sobol de premier ordre et les indices d'effet total pour l'année 2019 montrent que la variance de la consommation d'électricité est la principale cause de la variabilité de la RL en Occitanie, avec un indice de Sobol de premier ordre de 0.3804. En revanche, l'impact des productions éolienne et photovoltaïque sur la variabilité de la RL est presque négligeable.

Ensuite, la discussion étend l'analyse à la dynamique future de la RL en Occitanie. Elle utilise les objectifs de capacités VRE pour 2030, prévoyant des augmentations significatives des capacités éoliennes et solaires par rapport aux niveaux de 2019. L'analyse utilise l'écart-type pour mesurer la variabilité de la RL autour des valeurs moyennes. Les résultats montrent que des augmentations importantes des capacités intermittentes entraînent une forte augmentation de la variabilité de la RL en Occitanie. Avec une multiplication par trois des capacités éoliennes et solaires, la variabilité de la RL augmente de plus de 670 MW. Cela suggère que les augmentations prévues des capacités renouvelables auront un impact significatif sur les besoins futurs en flexibilité du système énergétique d'Occitanie.

En conclusion, il a été démontré dans ce chapitre que la prévision des besoins en flexibilité du système électrique peut être réalisée avec une faible erreur en utilisant une combinaison de décomposition de séries temporelles (CEEMDAN) et de réseau neuronal artificiel ConvLSTM-2D. Cette méthodologie permet de prévoir la RL horaire du système électrique de la région Occitanie sur une année entière avec des scores moyens de MAPE et RMSE respectivement de 3,02 % et 137,12 mégawatts (MW). Ces outils de prévision pourraient être utiles pour les acteurs du marché de l'électricité, permettant une meilleure programmation des unités de production, l'évitement des congestions du réseau et l'anticipation des fluctuations sur les marchés à terme. Des prévisions précises à différentes échelles de temps pourraient également aider les décideurs politiques à concevoir des politiques énergétiques efficaces et réalistes.

Cependant, les limitations techniques actuelles liées à l'entraînement des modèles d'apprentissage profond imposent une taille de fenêtre de prévision relativement petite, dans notre cas de vingt-quatre heures. Les prévisions produites par le modèle CEEMDAN-ConvLSTM-2D se basent uniquement sur des observations passées et ne peuvent donc pas prédire des chocs futurs sur la consommation ou la production d'électricité, comme une pandémie mondiale ou un changement rapide de la réglementation du marché électrique. Pour améliorer les performances prédictives de notre méthodologie, l'ajout de variables explicatives telles que les températures ou l'activité économique pourrait être envisagé.

Enfin, l'analyse de sensibilité basée sur la variance de la Charge Résiduelle en Occitanie suggère que les augmentations prévues des capacités VRE affecteront de plus en plus la

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variabilité de la RL. Ce développement attendu nécessitera des ajustements dans la conception du marché, une gestion améliorée du réseau, tant au niveau de la production que de la demande, et de nouveaux outils pour les acteurs du marché de l'électricité afin d'évaluer la valeur réelle des sources d'énergie variables et renouvelables.





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# FORECASTING POWER SYSTEM FLEXIBILITY REQUIREMENTS: A HYBRID DEEP- LEARNING APPROACH

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## 1. Introduction

### A. Context

Global energy-related CO<sub>2</sub> emissions stabilized in 2019, but still represented around 77% of the overall emissions. This stabilization is partially due to the world CO<sub>2</sub> emissions of the power sector declining by 1.3% between 2018 and 2019 [IEA, 2020]. Combining energy sobriety and renewable electricity generation has been identified as the most efficient path to cut-off emissions from the sector [Freeman, 1996 ; Johansson et al., 1996 ; Vassos et al., 1997 ; Dincer, 1999]. According to the International Renewable Energy Agency (IRENA), these efforts on the electricity sector only could cover up to 60% of the CO<sub>2</sub> emissions cuts needed by 2050 to reach climate goals [IRENA, 2019].

Among renewable energies, wind power and solar photovoltaics (PV) are the fastest growing technologies. Between 2000 and 2017, global installed onshore wind capacities have

been multiplied by 29, while solar PV capacities have been multiplied by 474 [IRENA, 2019]. However, these generation technologies are both intermittent and variable depending on weather conditions. Concurrently, Kirchhoff's laws imply that electricity generation and load must be always equalized in order to prevent serious damages on utilities, consumption devices or grid. Having a hard-to-predict and no controllable output, Variable and Renewable Energies (VRE) can thus be the source of technical issues on the power system, as well as high volatility on power markets [Nicolosi, 2010 ; Benhmad and Percebois, 2018 a,b]. Another problematic aspect of VRE integration is the optimal sizing of the generation fleet in a renewable based power system [Anoune et al., 2018]. Finally, grid extension planning can also be a dramatically affected by VRE integration [Schroeder et al. 2013]. Therefore, many researchers and stakeholders state that power systems incorporating more and more VRE must also be more and more flexible [Holttinen, et al., 2013 ; Oleinikova et al., 2015 ; Kondziella et al., 2016 ; Druce et al., 2016 ; Deetjen et al., 2017].

## B. Modeling flexibility requirements

Anticipating flexibility requirements is necessary to optimize the use of existing flexibility solutions. However, the increasing share of VRE capacities among power systems renders flexibility requirements assessment difficult since their output cannot be precisely forecasted more than a few days ahead. Additionally, modelling flexibility requirements can be hard because of the various temporal features involved in the concept. To tackle this issue, the Residual Load (RL) function is widely used as a proxy of flexibility requirements [Denholm et al., 2011 ; Wagner, 2012 ; Mikkola, 2016]. The RL corresponds to the amount of electricity consumption that is not covered by VRE generation, their production being generally prioritized either to benefit from weather conditions or because of specific regulation, like in

France [MTES, 2009]. In other terms, it represents the amount of load that must be managed by flexible means, such as controllable generation units or demand-response. Equations (1) and (2) describe the mathematical formulation of the RL function we will use in this paper.

$$(1) \textit{Residual Load} = \textit{Total Load} - \textit{VRE production}$$

$$(2) \textit{VRE production} = \textit{Solar PV production} + \textit{Wind production}$$

Using load and VRE production time-series, it is possible to calculate a RL curve that encompasses the different temporal aspects of flexibility requirements since time series can have both a high temporal granularity (i.e. hours or even minutes) and long time horizon (i.e. months or years). Therefore, predicting future flexibility requirements can be approximated by generating future RL time series.

To perform this, two major classes of prediction techniques exist: the ones using deterministic models, and the data-driven ones. Deterministic techniques are often based on the generation of large amounts of simulated weather data combined with techno-economic models. From then future load and VRE output time-series are calculated [Kondziella et al., 2016, Heggarty et al., 2019]. Albeit being absolutely transparent and very useful to explore many possible outcomes, either at short or long-time scales, deterministic techniques show two significant limitations: they usually require huge computational resources and rely on the modeler's assumptions, which sometimes can be unprecise or non-exhaustive [Deb et al., 2017].

Oppositely, data-driven forecasting techniques are used to reduce the number of assumptions incorporated to the model and focus as much as possible on recorded data to explore future developments of a phenomenon. In [Debnath et al., 2018], 483 scientific articles related to data-driven energy forecasting methods are reviewed. In this extensive



review, the authors categorize data-driven forecasting techniques into three classes: statistical methods, Computer Intelligence (CI) methods, and hybrid methods. Their findings are quite clear: hybrid methods have better forecasting performances than stand-alone methods, simply because mixing models together can effectively capture different aspects of a phenomenon and overcome stand-alone methods limitations. Notably, decomposition-based hybrid forecasting methods have been increasingly popular over the past years because of their ability to overcome high volatility and non-linearity specific to weather related time-series. In [Qian et al., 2019], 101 publications about decomposition-based forecasting methods are reviewed and the results show that the combination of decomposition and machine learning models can help reduce forecasting error.

### C. Review of recent literature on hybrid forecasting

Hybrid forecasting is currently attracting attention in multiple research fields. The data-driven nature of these methods renders them easily suitable for forecasting time-series in every domain. In [Cao et al., 2019], the authors decompose financial indexes time-series (S&P500, HSI, DAX, SSE) using CEEMDAN, and then train LSTM neural networks on each of these decompositions. This modeling framework systematically reduces the Root Mean Squared Error (RMSE) score of forecasts compared to a standalone LSTM model. In [Yang et al., 2020], Yang S. et al. also use an Empirical Mode Decomposition (EMD) variant to improve the forecasting performance of a LSTM network on carbon price time-series. Significant RMSE improvements are also reported when CEEMDAN is combined to LSTM networks for forecasting exchange rates [Lin et al., 2020 a] or crude oil prices [Lin et al., 2020 b] time-series.

Joining deep-learning approaches in a single ANN is also reported to improve the forecasting performances compared to stand-alone models. In particular, time-series forecasting can be drastically improved when Convolutional layers and LSTM layers are included in a single model (ConvLSTM). This technique is used in [Ibrahim et al., 2020] where short-term windspeed time-series forecasting is performed faster and more accurately than with stand-alone methods. Long-term PV power output can also be accurately predicted using a ConvLSTM model [Wang et al., 2019]. Another proof of the multiple time-scale prediction capabilities of ConvLSTM models is brought in [Xiao et al., 2020], where worldwide precipitations levels are accurately forecasted every 6 hours for one year. Finally, Coronati A. et al. propose in [Coronati et al., 2021] to use a 2DConvLSTM model to forecast the day-ahead Residual Demand Curve (here expressing the difference between demand and the aggregated competitors' supply offers) of the Iberian power system. Here again, significant error reductions are obtained compared to benchmark models.

## D. Paper contributions and structure

In this paper, we propose a novel hybrid approach to forecast the RL curve of any given power system, at different timescales. Precisely, we propose a RL time-series forecasting framework combining two techniques, namely Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN), and Convolutional and Long Short-Term Memory Artificial Neural Network (ConvLSTM ANN). We then use this framework to produce a one-year ahead hourly forecast of the residual load of a local power system, namely French region Occitanie. To our knowledge, using these two methods together have not been tested and documented yet in the energy forecasting literature. Moreover, we want to attract

attention on local power systems simply because both load profile and VRE production highly depend on local weather conditions. Providing RL forecasts on such geographical scale can also be useful for policy makers since more and more energy policies are designed and implemented on a local scale.

The paper is organized as follows. In section 2, we briefly introduce the basics of each individual method (CEEMDAN, LSTM and ConvLSTM-2D) before extensively describing the framework used in our study. In section 3, we present a numerical application of the proposed methodology on Occitanie power system and compare its forecasting results with the ones obtained with another more traditional modeling framework, namely ARIMA. To extend our analysis, we propose in Section 4 a variance-based sensitivity analysis of Occitanie RL with changes in VRE capacities. Section 5 is dedicated to conclusion and discussion of other research avenues on this topic. this topic.

## 2. Methodology

### A. Empirical Mode Decomposition (EMD) and its extensions

EMD is a signal-processing method first introduced in [Huang et al., 1998] that can also be useful for time-series analysis. The general purpose of this method is to overcome non-linearity and non-stationarity in time-series to better analyze or predict them. To achieve this, EMD consists in decomposing a non-linear and non-stationary time-series into a set of stationary subseries called Intrinsic Mode Functions (IMFs), plus a residue. The IMFs represent the oscillatory patterns included in the original series, while the residues can be interpreted as the series long term trend. By simply summing all the obtained IMFs and

residue, one can recover the original time-series. As opposed to wavelet-based decomposition, EMD is a purely empirical method which is particularly well suited for indeterministic problems analysis. The decomposition algorithm is the following:

1. Identify all local extrema of the original time-series and connect them to obtain the upper and lower envelopes.
2. Calculate the average envelope and subtract it from the original series to get the first component. These first two actions are known as the *sifting process*.
3. This first component becomes the new series to sift. Repeat actions 1. and 2. until finding an IMF, i.e., a function having the following properties:
  - The difference between the number of local extrema and zero-crossings is at most 1.
  - The mean value between upper and lower envelopes is 0.
4. Once the first IMF is extracted, subtract it from the original time-series, and repeat the sifting process on this new series to identify the next IMF.
5. Once all IMFs have been extracted using the sifting process, it should remain only a monotonic function in which no more IMF can be extracted. This last function is the residue.

The very advantage of this method is to empirically transform a nonlinear, non-stationary and therefore hard-to-predict time-series into a set of IMFs which are easier to predict, due to their stationary properties. However, EMD itself presents an issue known as the *mode-mixing problem*, i.e., the fact that inside an IMF two different oscillatory patterns can overlap, or that the same oscillatory pattern can appear in multiple IMFs. To solve this issue, EMD has been improved to become first *Ensemble Empirical Mode Decomposition* (EEMD) [Wu et al., 2009] and then *Complete Ensemble Empirical Mode Decomposition with Adaptive Noise* (CEEMDAN) [Torres et al., 2011], which both benefit from statistical properties of white-noises to overcome the mode-mixing problem. Basically, CEEMDAN adds a different white-

noise series in every step of the sifting process to make sure all extracted IMFs represent a single and specific oscillatory pattern comprised in the original time-series. However, CEEMDAN is a high-consuming computational method which cannot be computed parallelly.

## B. Artificial Neural Networks

### i. Basic principles

Artificial Neural Networks (ANN) are a widely used machine-learning architecture reported to both handle well non-linearity and be universal approximators [Deb et al., 2018 ; Cai et al., 2019]. ANN models can be described as an attempt to mimic a mammal brain's architecture thus they are made of *neurons* connected in *layers* via *weight vectors*. Neurons can be understood as data processing units, each of them performing calculation with specific *activation functions*. A typical ANN is made of neurons organized in three different layers: an input layer, a hidden layer, and an output layer. Neurons inside a layer are connected to the next layer via weight vectors which parameters can be interpreted as connection intensities between data processing-units i.e., synapses. Through a process called *back-propagation*, data are passed in each layer of the network again and again, and weights vectors are each time updated with the aim of minimizing a given loss function<sup>5</sup>. ANNs can be used for a wide range of problems, from image classification to text generation, including among others audio and video synthesis, data mining and time series forecasting. A graph illustrating an ANN architecture can be found in Figure 1.

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<sup>5</sup> Here we refer to a *supervised learning* method, which provides the network with a well-defined target function to evaluate its weights updates, as opposed to *unsupervised learning* methods.

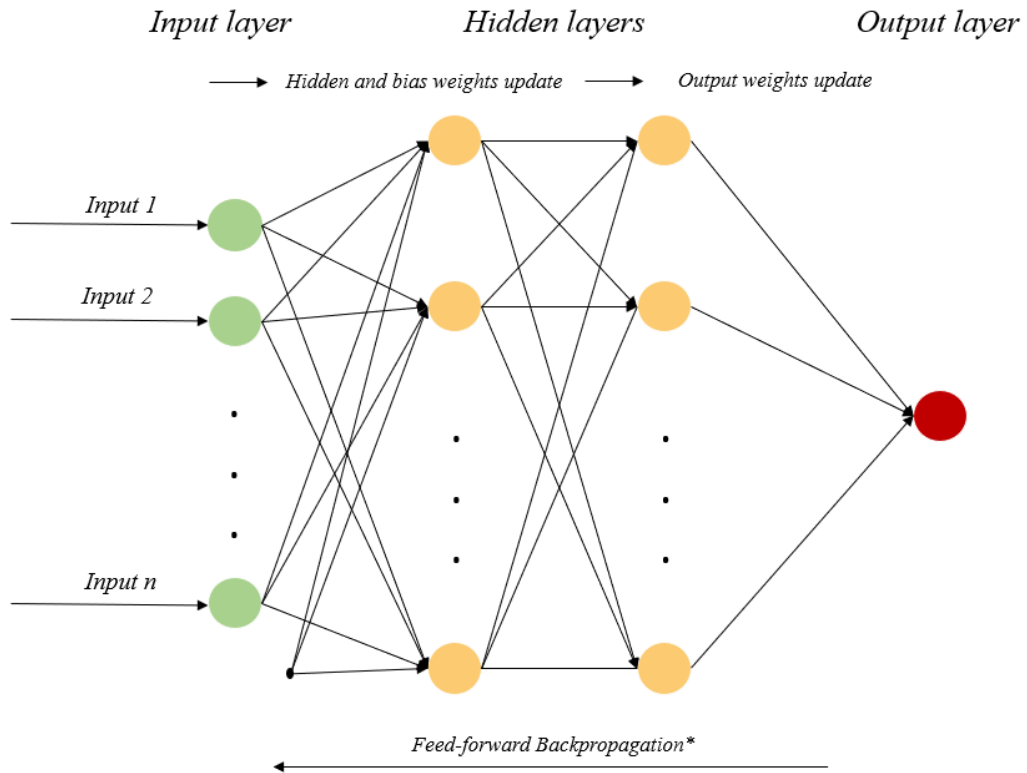


Figure 1 : Typical architecture of a fully connected two hidden layers ANN.

\*Each time data flows along each layer of the network, weights and bias vectors are updated. To make sure the weights updating process converges towards the minimization of the loss function, the gradient of the loss function is computed with respect to the state of the whole network at the end of each cycle (or *epoch*).

## ii. Recurrent Neural Networks (RNN) and Long-Short Term Memory (LSTM)

Recurrent Neural Networks (RNN) are a type of ANN specifically designed to perform tasks using temporal data. The architecture of a RNN is close to the ANN, but differences in that neurons in the hidden layers are connected to each other in a directed graph ordered in a

temporal sequence. This architecture makes RNN able to keep track of the temporal order in a dataset while processing it, and therefore efficiently capture temporal dependencies in time series data of various lengths [Tealab, 2018]. Unlike most of traditional time-series forecasting methods, the forecasting equation in a RNN is framed into a sequence-forecasting problem (or structural forecast) and not a single-step forecast problem, allowing both short and long-time forecasting. However, RNN undergo a strong limitation when it comes to train them over long and complex data, an issue known as the vanishing-gradient problem. This issue can emerge in models using backpropagation because of the gradient being computed as the partial derivative of the loss function with respect to the state of weights vectors in each iteration. RNN treating data sequentially, the error signal provided by the gradient is diluted as the temporal gap between past relevant data and next forecast increases, rendering the network difficult to train over long temporal sequences [Bengio et al., 1994]. Oppositely, the gradient exploding problem, also reported while training RNNs, refers to the error signal being artificially inflated at each training epoch, potentially resulting also in an untrainable network.

An answer to the vanishing/exploding gradient problem has been formulated in [Hochreiter et al., 1997] under the name of Long-Short Term Memory (LSTM) units. LSTM are a particular RNN architecture which includes a set of logical operators called *gates* inside the hidden recurrent neurons (or the *memory cell*). The role of logical gates is to select whether an incoming data should be used for the next prediction and stored into the memory cell or not. This process allows LSTM to capture both long-and short-term dependencies without being limited by the size of the dataset or the network. LSTM networks are therefore particularly efficient for predicting any type of temporal sequence, such as speech, text, or simply unidimensional time-series. It is also possible to feed a LSTM network with multidimensional time-series thus to include exogenous variables in addition to past recorded

data. Mathematical details of the working principles of LSTM units can be found in Appendix 1.A.

### iii. Convolutional Long Short-Term Memory (ConvLSTM)

A recent approach to enhance LSTM predictive abilities is to combine it with a Convolutional Neural Network (CNN) [LeCun et al., 1995]. CNNs can be used with a lot of different data types but are particularly efficient when performing visual tasks like image classification or video editing. Instead of analyzing temporal correlations in time-series like LSTM, CNNs use *convolutional windows*, which act as magnifying lenses moving around to recognize repeating patterns in a labeled image or sequence of images. The idea behind ConvLSTM models is therefore to enhance LSTM unit's memory capabilities by applying a *visual treatment* of the data in addition to the sequential modeling of the data itself. Using 2D representations (e.g., simply graphs over time) of sequences of time-series data and flowing them into a ConvLSTM-2D network might thus provide enhanced speed and forecasting accuracy compared to stand-alone LSTM models.

Equations describing the mechanics behind a ConvLSTM model are provided in Appendix 1.B.

## C. Proposed methodology

In this paper, we propose to use the previously described methods consecutively to forecast a given power system residual load curve. Our goal is to assess the flexibility



requirements at multiple time scales thus we will use time-series data with hourly time granularity to forecast both one day and one year-ahead RL. Our past sequence of RL will be simply built using past consumption and past VRE production. Since consumption and VRE production time series are both non-linear, non-stationary and highly volatile, our constructed RL time series will need to be decomposed to be more easily forecasted. Therefore, we first apply CEEMDAN decomposition to the RL time-series to obtain a set of IMFs that presents useful stationarity and oscillatory properties. In this study, precision is privileged over speed, that is why we do not specify any target number of IMFs or maximum sifting operations for the CEEMDAN process. The only stopping criterion used is a *S number* put at 5. The *S* number is a parameter that represents the number of iterative sifting processes ending with an IMF before switching to the next. The resulting IMFs and the past sequence of RL will then be used as inputs in a multivariate ConvLSTM-2D model. The idea here is to analyze the temporal dependencies between oscillatory patterns contained in the RL time-series itself to enhance the forecasting performance of the model.

In traditional one-step ahead forecasting approaches, the error of the first forecasted step is propagated over and over all along the forecasting period, which generally leads to poor forecasting performances as the forecasting horizon becomes more distant. To avoid this issue, we frame our problem as a sequence-to-sequence (or *seq2seq*) forecasting problem, that can be described by Equation 3:

$$(3) \hat{Y}_{t+1|t}, \dots, \hat{Y}_{t+L|t} = f(Y_t, Y_{t-1}, \dots, IMF_{1,t}, IMF_{1,t-1}, \dots, IMF_{n,t}, IMF_{n,t-1}, \dots)$$

Where  $Y_t, Y_{t-1}, \dots$  is a past sequence of RL observations,  $IMF_{n,t}, IMF_{n,t-1}, \dots$  is a past sequence of IMF  $n$  data extracted from the original RL time-series, and  $\hat{Y}_{t+1|t}, \dots, \hat{Y}_{t+L|t}$  is the

RL forecasted sequence up to time horizon  $L$ . In our methodology, we choose to produce forecasting sequences of 24 hours to represent full days of RL. Therefore, a full forecasted day of RL can be represented by the following equation:

$$(4) \hat{D}_{t+1|t} = \hat{Y}_{t+1|t}, \dots, \hat{Y}_{t+24|t}$$

To enhance the forecasting performances of our model and to get closer from a real-world situation where daily incoming data can be used to improve forecasts of the following days, we will use *walk-forward validation* of the model during its training. This means that to calibrate its weights and bias parameters, the model will incorporate actual data to its training history as they become available over time. In other terms, every time the model produces a daily sequence forecast  $\hat{D}_{t+1}$ , actual data from that day will be added to the history to perform the next sequence forecast  $\hat{D}_{t+1}$ . It is to be noted that this process requires to first decompose our full time-series into stacks of 24 hours, which can only work if the input time-series lengths are multiple of 24.

In addition to the graph proposed in Figure 2., we want to provide here a detailed explanation of the way our model is trained. The decomposed and stacked time-series data are feed to a two layered ANN. The goal of the first ConvLSTM layer is to capture temporal dependencies among data in a visual way. To achieve this, the 24-hours stacks of 1D time-series data are transformed in a time-series of 2D images, in which each image is a 24-hour length frame of RL and RL IMFs curves. Flowing along all the images, the network updates its weights and bias vectors a first time and performs a forecast of the next 24-hour length image. This operation is realized using convolution operators inside LSTM units (see

Appendix 1.B.), which allows the network to capture both spatial and temporal dependencies between pixels inside consecutive images.

In a second time, the forecasted image is then passed through a *Flatten layer*, which role is to reduce the image dimensionality to re-transform it into a 1D tensor vector of spatiotemporal dependencies between the previously graphed datapoints. Then, temporal correlations within this vector are analyzed in depth by a simple LSTM layer, and weights and bias vectors of the ANN are updated a second time. Finally, a *Dense layer*, which is the equivalent of an output layer in code language, will perform the desired forecast of successive 24 RL datapoints. The forecasted points are then compared to actual data of the same period to compute the loss. Parallely, actual data are added to the history to provide the most recent information to the network for the next forecast. This cycle continues until reaching the last forecasting period and once all forecasts are done, a *training epoch* ends. The number of training epochs will vary with the forecasting precision sought and the available time and computational resources.

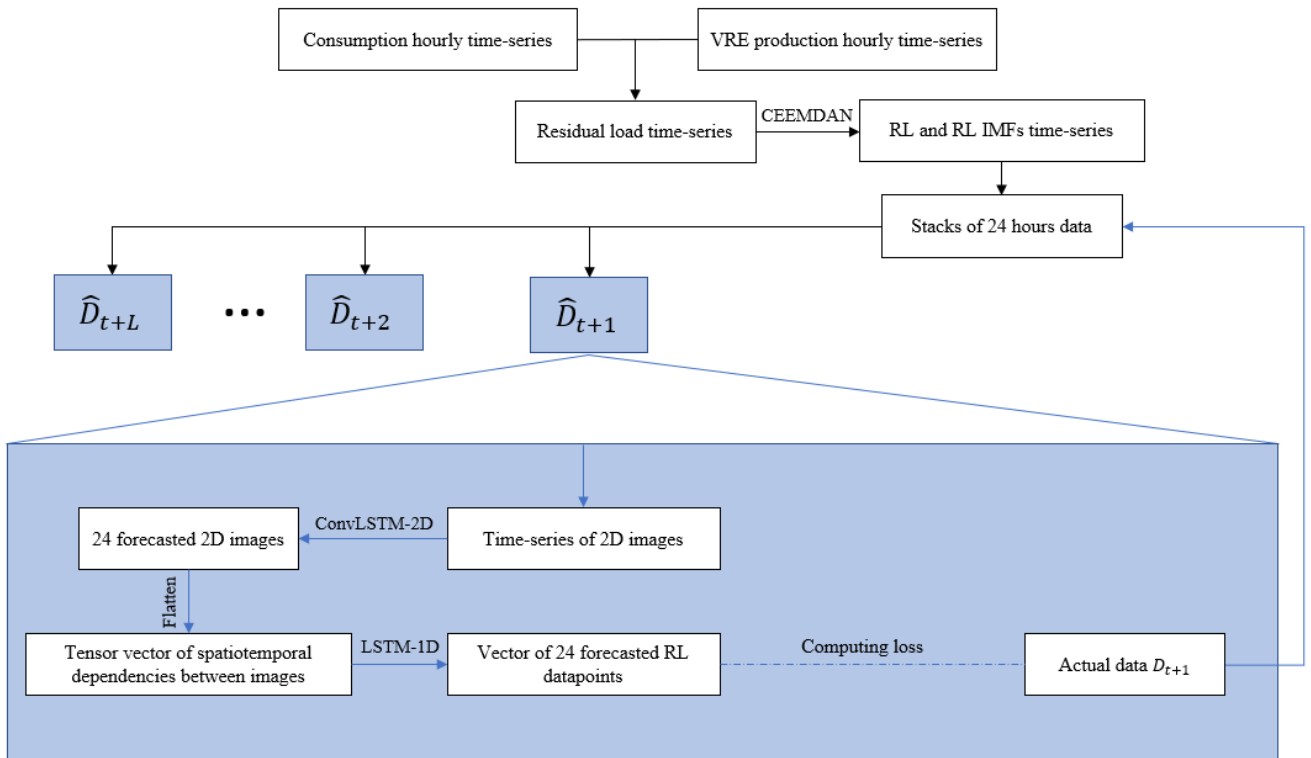


Figure 2 : The CEEMDAN-ConvLSTM-2D Residual Load forecasting framework

### 3. Application to Occitanie region

#### A. The Occitanie region: A French pioneer of VRE implementation

The implementation of Variable and Renewable Energy sources is not homogeneously spread amongst power systems. In a medium-sized country like France, the various climate conditions observed across the metropolitan territory had for consequence an uneven development of VRE capacities between regions. Indeed, not all French regions offer the same potential for the development of wind and solar photovoltaics (PV) generation capacities. Consequently, the most attractive sites have been privileged first since the beginning of the fast development of VRE capacities in France.

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Located in the south of France, Occitanie region is one of the pioneers of renewable energies development on the French territory. This can be explained by the very attractive climate conditions the region has to offer for VRE implementation. In terms of sunlight, Occitanie benefits from a very high number of sunny hours (around 2 600 hours in average) each year. Being also a Mediterranean coastal region, Occitanie is gifted with regular and vigorous winds all over the year. As a consequence, load factors of wind and PV are in average higher in this region than elsewhere in France (respectively 26.1% and 14.5% for the year 2019). Therefore, the region has witnessed a rapid development of both wind and solar PV capacities over the past decade: between 2008 and 2019, wind generation capacities have increased each year by 9.87% in average, and this figure reaches 64.99% for PV capacities. Thus, by the end of 2019, respectively 1.6 GW and 2 GW of wind and PV capacities were installed on the Occitanie territory, resulting in a respective coverage of 8.45% and 6.28% of the region's electricity consumption. The rest of the region's electricity production is dominated by hydroelectricity (5.3 GW installed capacity) and nuclear (2.6 GW installed capacity)<sup>6</sup>.

Besides the intense development of VRE in Occitanie, the region is also a relevant case-study for a study on flexibility requirements for two reasons. The first one is the 2 GW interconnection transmission line connected to the Spanish power system, in which more than 20 TWh of electricity transited in 2017. Such international transmission lines are becoming crucial in power systems integrating large shares of renewables, because they help to balance load and electricity generation by benefitting from differences in both consumption and generation profiles of the two countries.

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<sup>6</sup> Figures are calculated using data from Open Data Réseaux Energies (ODRE), the French energy open-data platform (<https://opendata.reseaux-energies.fr/pages/accueil/>).

Finally, Occitanie has made a political goal to become “*the first positive energy European region*”, meaning that public investments towards renewable generation technologies, storage or energy efficiency are expected to grow each year. For instance, in May 2019, the Occitanie Economic Development Agency (AD’OCC) announced a 150 million euros plan to develop hydrogen infrastructures, almost one year before the same kind of plan was proposed at the European level. For all of these reasons, we considered that using Occitanie data was highly relevant for the flexibility requirements study conducted in this article.

## B. Dataset presentation

Technical aspects of our proposed RL forecasting methodology having been detailed in Section 2; we now want to assess its potential on a real-world case study. The chosen geographical perimeter for this study is the French region of Occitanie, and we will consider for the sake of simplicity that its power system is a copper plate (*i.e.*, the regional power system is supposed to have no interconnections with its neighboring regions or countries.)

The website Open Data Réseaux Energies (ODRE) is an open-data platform where French energy grid operators share energy-related data with the public<sup>7</sup>. On this platform, time-series of Occitanie electricity consumption and production can be freely downloaded. Since deep learning models are reputed to be very data-intensive, we choose to provide our network with the greatest available amount of data the open-data website has to offer by the beginning of 2020.

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<sup>7</sup> Open-Data Réseaux Energies (ODRE) website: <https://opendata.reseaux-energies.fr>. The data used in the paper are coming from the *Données éCO2mix régionales et définitives* dataset.

Therefore, the data we use in this study are the following:

- Aggregated Occitanie hourly electricity consumption between 01/01/2013 00:00 and 31/12/2019 00:00 (61 322 datapoints)
- Aggregated Occitanie hourly wind electricity production between 01/01/2013 00:00 and 31/12/2019 00:00 (61 322 datapoints)
- Aggregated Occitanie hourly solar PV electricity production between 01/01/2013 00:00 and 31/12/2019 00:00 (61 322 datapoints)

As expected, multiple seasonal patterns can be directly derived by a graphical analysis of Occitanie electricity demand (see Figure 3.). The series seems to have a slightly increasing trend, with a mean of 42.87 GW and a relatively high standard deviation of around 1 GW (see Table 2.).

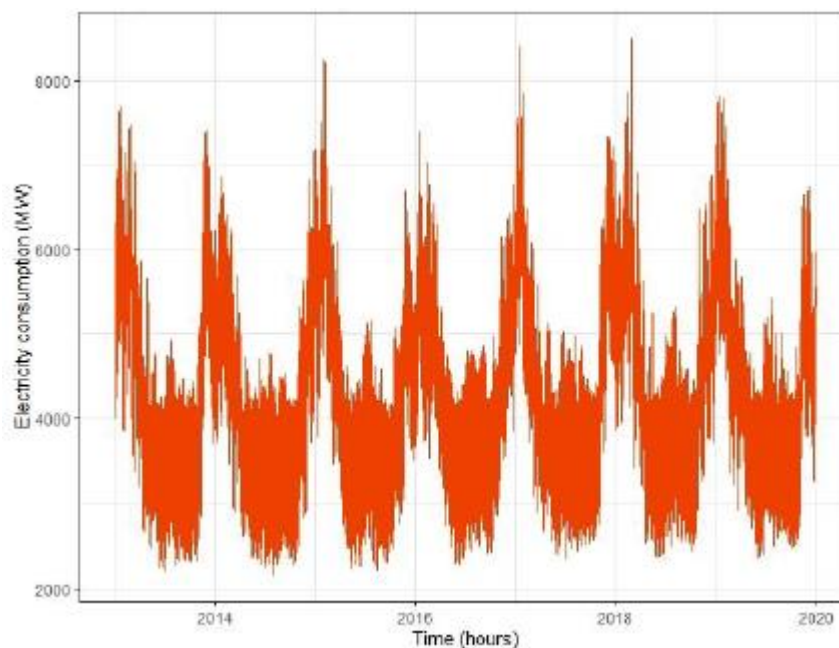


Figure 3 : Hourly Occitanie electricity consumption between 2013 and 2019

Wind and PV electricity generation time-series of Occitanie region display clear seasonal patterns too, yet a graphical representation of these data suggests definitely increasing trends for the two series (see Figures 4.). Obviously, these trends are encompassing the previously mentioned VRE increasing capacities the region has known over the past decade. They do represent a significant difficulty to harness for the model, simply because the long-term evolution of VRE penetration in this region is still subject to a lot of political, economic, technological, and environmental uncertainties. Besides their difficult long-term trend identification, both series present a high standard deviation compared to their mean, which is an expected feature of weather-dependent processes (see Table 2).

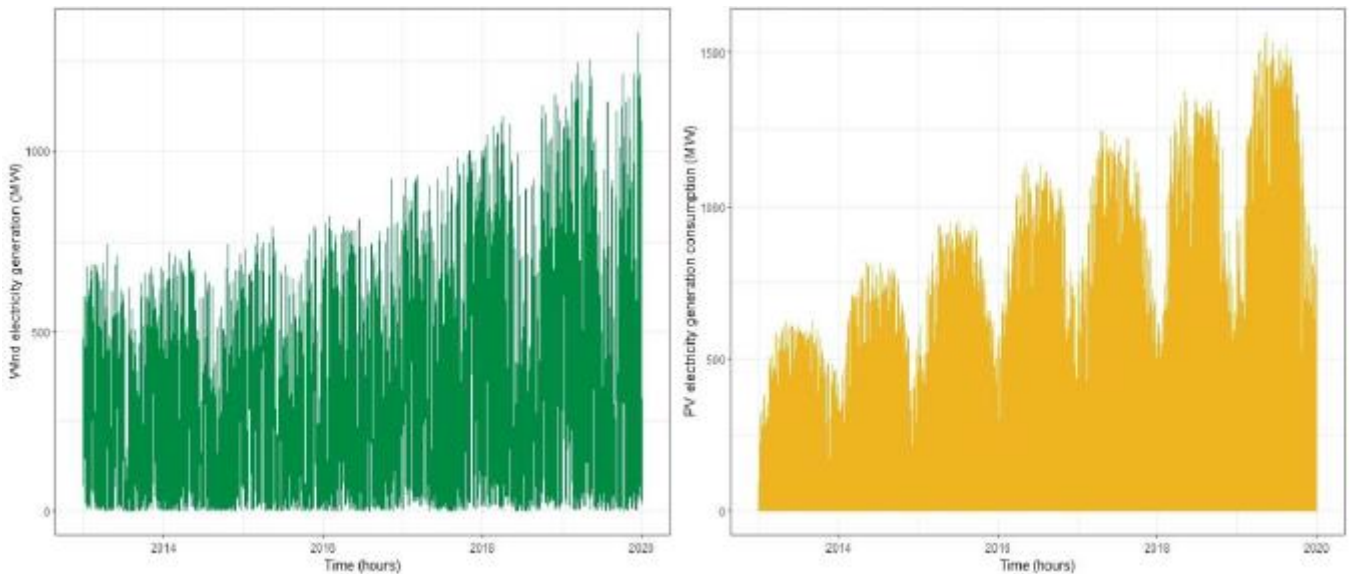


Figure 4. Hourly Occitanie wind (left) and PV (right) electricity generation 2013-2019

These data are then concatenated in a RL time-series using equations (1) and (2). The resulting time-series is largely influenced by the initial electricity consumption data and therefore presents the same strong multiple seasonal patterns (see Figure 5. upper-left corner



chart). The slight increase of standard deviation compared to the electricity consumption time-series illustrates well the relatively small contribution of VRE production to satisfy the region's significant electricity demand (see Table 2.).

Time-series	Unit	Length	Min.	1 <sup>st</sup> Qu.	3 <sup>rd</sup> Qu.	Max.	Mean	Median	Std. Dev.
Consumption	MW	61 344	2 167	3 526	4 963	8 488	4 287	4 100	1 045.99
Wind production	MW	61 344	0	87	493	1 331	316	264	257.28
PV production	MW	61 344	0	0	345	1 568	205	2	314.78
Residual Load	MW	61 344	612	2 957	4 465	8 196	3 765	3 553	1 079.54

Table 2 : Descriptive statistics of Occitanie historical residual load variables between 2013 and 2019

Using R programming language and R package *EMD* [Kim et al., 2018], we perform the CEEMDAN decomposition of our RL time-series and provide a graphical view in Figure 6. It is worth mentioning that CEEMDAN is a time-consuming process that requires to be done only one time per modeled time-series.

It is a bit difficult to give a proper meaning to all the extracted IMFs, as they are ultimately only representations of averaged local extrema included in the original series. However, some seasonal patterns seem to emerge in the last three IMFs : for instance, in IMF 14, the variations between five consecutive extrema might represent the seasonal complementarity between wind power production, which is generally more intense during winter, and the summer higher intensity of PV power production. In addition, the increased amplitude of this IMF for years 2015 and 2017 could be interpreted as a more pronounced seasonal electricity consumption gradient. At the end, the only strongly reliable interpretation we can make of this graph of decomposed RL is that the Residual really encompasses the typical electricity consumption seasonal pattern.

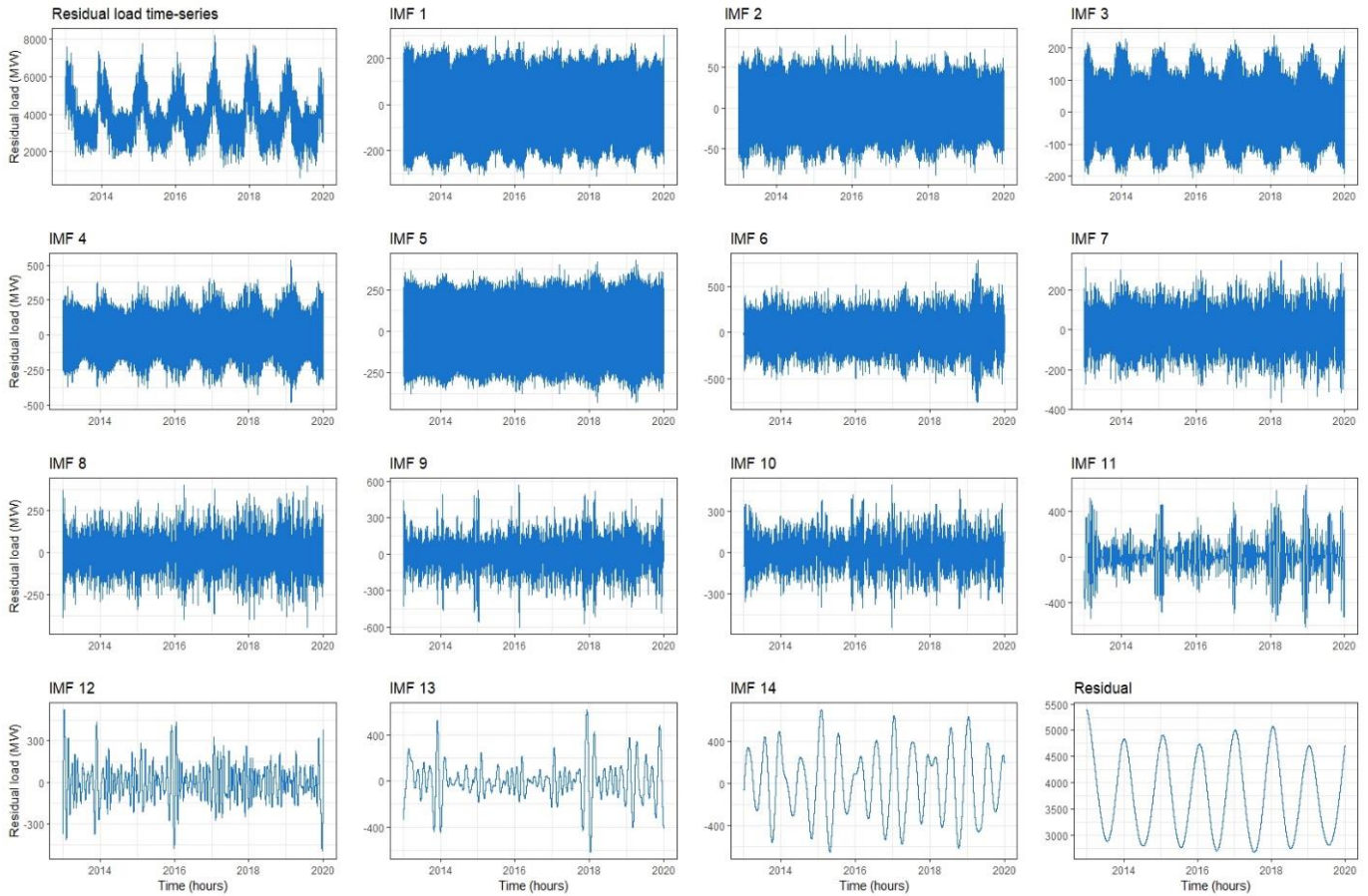


Figure 5 : CEEMDAN decomposition of Occitanie power system residual load

### C. Compared models

In the energy industry and more generally in econometrics, *AutoRegressive Integrated Moving Average* (ARIMA) are a well-known class of time-series forecasting models first introduced by Box G. and Jenkins G. in 1970 [71]. ARIMA models have shown satisfying short-term forecasting results over the past decades but are strongly limited by their structure for long-term prediction. Indeed, in ARIMA models, the forecasting steps are inevitably performed sequentially, resulting in strong error propagation as the forecasting horizon increases. This can be a particular issue in the electricity field where having accurate forecasts for the entire next day, week or even year can be critical for system operation and planning. To counter this issue, specific ARIMA models can be calibrated to forecast only a single or a few steps ahead. For instance, to predict an entire day ahead of hourly

consumption with the ARIMA framework, one can build twenty-four ARIMA models specifically designed to forecast every hour of the day. Although being eventually more precise, this approach is more resource consuming and approaches its limits when it comes to forecast an entire year of hourly time-series. Oppositely, neural network sequence-to-sequence forecasting allows to forecast entire time sequences at once, and thus could be a way to avoid the step-to-step forecasting error propagation issue using only one model.

To assess the performance of our proposed methodology, we will compare the results obtained regarding several metrics to three other forecasting frameworks, namely ARIMA, LSTM and CEEMDAN-LSTM<sup>8</sup>. The structure and parameters of each model are the following:

- ARIMA : ARIMA(4,1,2)
- Univariate seq2seq LSTM : 1 LSTM layer with 400 neurons, each of them having a Rectified Linear Unit (ReLU) activation function. Adaptive Moment Estimation (ADAM) optimizer and Mean Squared Error (MSE) loss function. Online training for 30 epochs.
- Multivariate seq2seq CEEMDAN-LSTM : 1 LSTM layer with 400 neurons with ReLU activation function. ADAM optimizer and MSE loss function. Batch training for 300 epochs with a batch size of 24. L2 weights and bias regularizer.
- Multivariate seq2seq CEEMDAN-ConvLSTM-2D : 1 ConvLSTM layer with 24 kernel features of size (1,2) and 1 LSTM layer with 400 neurons, both with ReLU activation function. ADAM optimizer and MSE loss function. Batch training for 300

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<sup>8</sup> The ARIMA model is built using the *forecast* R package [Hyndman, 2020] while deep-learning models were encoded using Python 3.7 programming language with Tensorflow and Keras [Cholet et al., 2015] frameworks. Many coding issues were resolved thanks to Jason Brownlee's book [Brownlee et al., 2021] and blogposts. All models are computed with the professional laptop mentioned in Section 4.1., and deep-learning models' hyperparameters are tuned using a trial-and-error approach.

epochs with a batch size of 24. Training early stopping with Validation Loss monitored and 70 epochs of patience.

## D. Results

The chosen comparison metrics between the different forecasting results and the actual values are the Mean Absolute Percentage Error (MAPE) and the Root Mean Squared Error (RMSE) (see Equations 5 and 6), the last having the advantage of providing the forecasting error in the same unit as input data. We propose to compare the MAPE and RMSE of the first forecasted 24 hours and of the whole forecasted period (i.e., 8 736 hours), which correspond to a full year (minus a day).

$$(5) \text{ MAPE} = \frac{100}{n} \sum_{i=1}^n \left| \frac{y_i - \hat{y}_i}{y_i} \right|$$

$$(6) \text{ RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}$$

It is very important to recall that since deep-learning models training is a stochastic process, the RMSE results can slightly vary from one training session to another. Therefore, we present here the best results obtained per model, each one of them having been trained at least ten times. As presented in Table 3., models are also compared in terms of computational time. Precisely, for all models involving deep-learning, we compare the average computation time of one training epoch, while the overall computational time of ARIMA model is given.

<i>Model</i>	<i>MAPE 1<sup>rst</sup> 24h</i>	<i>MAPE 8 736h</i>	<i>RMSE 1<sup>rst</sup> 24h</i>	<i>RMSE 8 736h</i>	<i>Computation time (seconds/epoch)</i>
<i>ARIMA</i>	6.85%	57.96%	437,79 MW	1873,90 MW	10" (overall time)
<i>LSTM</i>	8,00%	18.42%	471,62 MW	765,59 MW	309"/epoch
<i>CEEMDAN-LSTM</i>	5.80%	28.00%	404,06 MW	980,63 MW	18"/epoch
<i>CEEMDAN-ConvLSTM-2D</i>	3.79%	3.02%	260,33 MW	137,12 MW	208"epoch

Table 3 : Performance metrics of compared models

The results of our comparison suggest a better performance of the CEEMDAN-ConvLSTM-2D model at both close and distant forecasting horizons. Indeed, the model performs an almost-full year of hourly RL forecast with a MAPE of 3.02% and a RMSE of 137.12 MW, which are the lowest scores observed in our comparison. Though, the required training time to produce this forecast is still consequent (more than 17 hours and a half in total for 300 training epochs), but below the second best-long time-performing model namely Univariate seq2seq LSTM (referred here simply as LSTM). At a short timescale (i.e. the first forecasted 24 hours), the CEEMDAN-ConvLSTM-2D model also performs the best, reducing the RMSE score by more than 55% compared to the second-best performing model namely CEEMDAN-LSTM. However, it is to be noted that the required time to train the CEEMDAN-LSTM model is much lower than other models based on LSTM ANNs. Still, the algorithms tested here are designed only to produce seq2seq forecasts with a full forecasting horizon of 8 736 periods ahead, and therefore do not especially aim to produce day-ahead forecasts as fast as possible. To better apprehend the forecasting results obtained with the four tested models, we provide a graphical comparison in Figure 6.

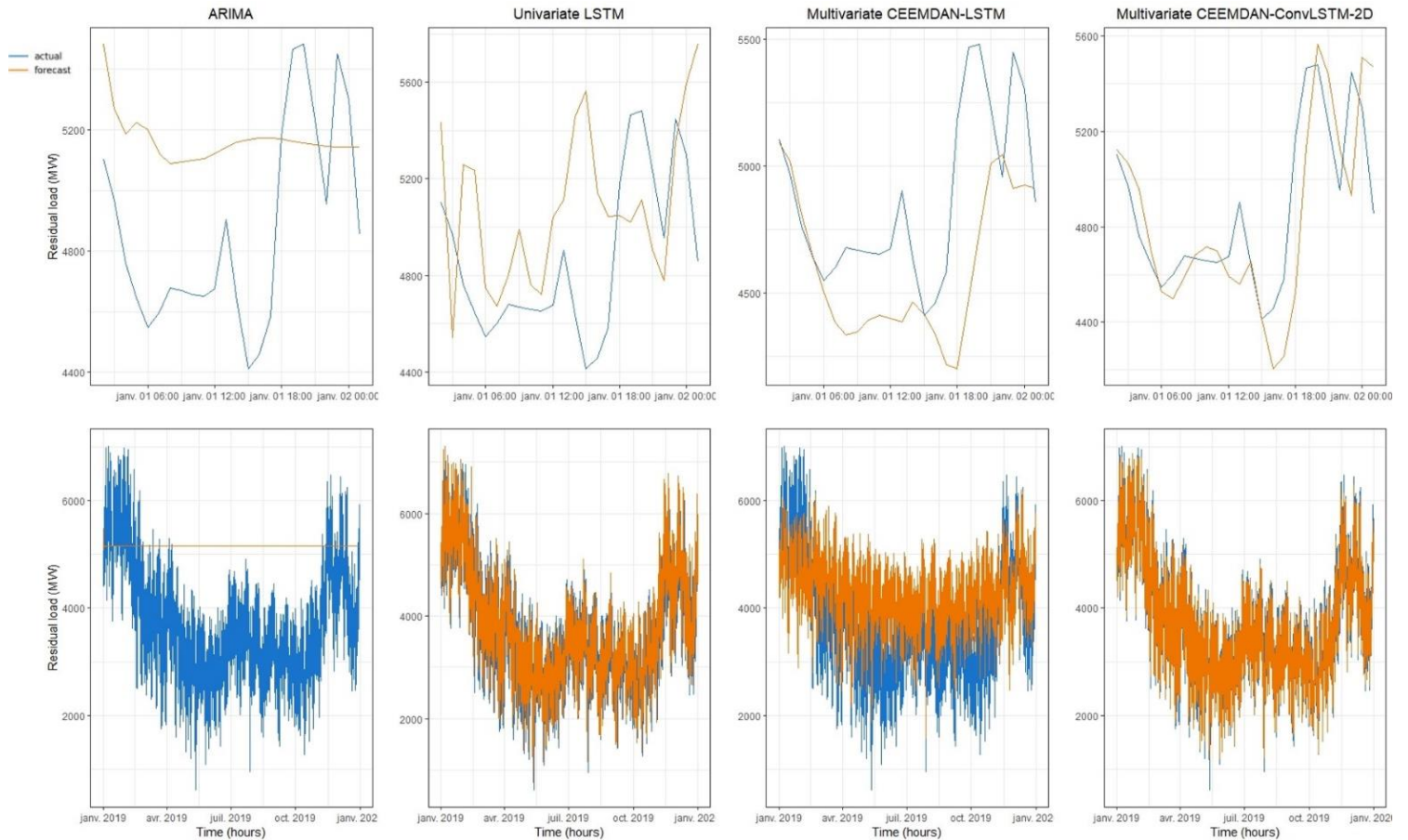


Figure 6 : Graphical comparison of forecasting results against actual for the four tested models

First 24 hours forecasts (i.e. forecasts for the 1<sup>st</sup> of January 2019) are represented in the upper line of charts, while the full forecasted period (i.e. from the 1<sup>st</sup> of January 2019 to the 31<sup>st</sup> of December 2019) is represented in the lower line of charts.

As a conclusion, the consistent forecasting performances of the CEEMDAN-ConvLSTM-2D framework over time make it very suitable to build realistic baseline scenarios of hourly residual load dynamics. By increasing the forecasting window size, one could actually use this method to explore out-of-the-sample hourly long-term developments of Occitanie RL with a relative confidence. Of course, such a data-based method does not account for eventual shocks such as specific policy implementation, market structural changes or technology improvements that did not occurred in the past. Therefore, using the

CEEMDAN-ConvLSTM-2D framework should always be regarded as a *Business-As-Usual* (BAU) forecasting tool.

## 4. Variance-based sensitivity analysis

### A. Sobol indexes of 2019 Occitanie RL

In this section, we are exploring in which ways the increase of VRE capacities might affect the Occitanie Residual Load variability. First, we want to know to what extent the observed past RL variability is affected by VRE production variability. The Sobol index is a useful tool in variance-based sensitivity analysis because it quantifies how much the variance of a given output series is caused by the variance of each of the input variables. In our case, the output variable is the hourly Occitanie Residual Load, and the input variables are the hourly electricity consumption, wind production and solar PV production. Calculating the first order Sobol indexes of each of these variables will thus help us to quantify the impact of their own variance on the variance of our Occitanie RL series. Another advantage of this technique is that cross-Sobol indexes (Total-effect Sobol indexes) can be calculated to measure the effects of interactions between variables in addition to their own unilateral effect. To make sure this analysis is as relevant as possible, we chose to use here only the most recent data available which corresponds to year 2019. The results of this analysis are presented in Table 4.

Input Variable	First order Sobol Index	Std. Err.	Total-effect Sobol Index	Std. Err.
Consumption	0.3804	0.0150	0.9940	0.02812
Wind production	0.0009	0.0004	0.0009	0.00002
Solar PV production	0.0019	0.0189	0.6140	0.00973

Table 4 : First order and Total-effect Sobol indexes of Occitanie electricity consumption, wind production, and solar PV production with respect to the hourly Occitanie Residual Load of year 2019

The attentive reader will note that the sum of all first order Sobol indexes is less than 100%. This is due to the fact that one must also account for higher order indexes which quantify the simultaneous contribution of the variance of two (or more) variables to the variance of the output variable. For the sake of clarity, these higher order indexes are not included in Table 4. Oppositely, the sum of all Total-effect Sobol indexes is more than 100%, simply because, as mentioned above, these indexes account also for the interactions between variables.

Overall, the results of this calculation are quite unambiguous: nowadays, the impacts of the intermittent renewable production variables' variance on the Residual Load variance are almost negligible (respectively 0.0009 and 0.0019 for first order Sobol indexes of wind and solar PV production), and much of the Occitanie RL variance is caused by the variance in electricity consumption (first order Sobol index of 0.3804). The total-effect Sobol indexes are more difficult to interpret, as it is quite unclear what the interactions between the input variables actually are. Still, these indexes also highlight the predominance of the electricity consumption variance as the main driver of Residual Load variability.

## **B. Sensitivity analysis of Occitanie RL to changes in VRE capacities**

To extend our analysis to future Occitanie Residual Load dynamics, we finally provide the reader with a variance-based sensitivity analysis of Occitanie RL with changes in intermittent



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energy production capacities. Following the idea of flexibility requirements assessment, we want to know how the Residual Load variability is affected by the inclusion of more VRE units into the electricity generation mix. This analysis proposes to use actual VRE capacities targets for 2030, as presented in [Région Occitanie, 2020]. In this local energy policy document, targets for onshore wind capacities are set to 3 600 MW in

2030 and 6 300 MW for solar PV capacities. These targets represent capacity increases of respectively 121% and 213% compared to 2019 levels.

In our analysis, we will use the Standard Deviation metric as an indicator of Occitanie RL variability around mean values. Since we are more interested in the impact of VRE capacities increases, we assume that electricity consumption within the region remains unchanged. Here again we will use only the most recent data available i.e., those from year 2019. Using installed generation capacities data, we compute the hourly local load factor of both wind and solar PV technologies for the full year 2019. Then, we propose to increase the capacities of wind and PV technologies up to a factor 200%, and see how the Occitanie RL Standard Deviation reacts using the following equation:

$$(7) \Delta St. Dev_{Occitanie RL} = \sqrt{\frac{\sum_i^N ((D - (\Delta C_W * L_W + \Delta C_{PV} * L_{PV}))_i - (D - (\Delta C_W * L_W + \Delta C_{PV} * L_{PV})))^2}{N-1}}$$

With  $D$  the electricity demand (consumption),  $C$  and  $L$  respectively the installed capacity and load factor of technology  $W$  (Wind) and  $PV$  (Solar PV), and  $N$  the sample size.

The results of this sensitivity analysis are presented in Figure 7. What we observe first is that significant increases in intermittent capacities induce an intense spike in Occitanie RL variability. Precisely, with no changes in intermittent capacities, the Occitanie RL Standard Deviation is 1090.78 MW. When both wind and solar PV capacities are multiplied by a factor 3 (+200%), the Occitanie RL Standard Deviation becomes 1767.50 MW, which is more than a 670 MW increase in variability. For the expected case where wind capacities increase by 120% and PV capacities by 200%, the Occitanie RL variability is 1672.82 MW, or more than 580 MW of flexibility needs compared to the 2019 level. Therefore, this result strongly suggests that the planned increases in intermittent renewables capacities will have a significant impact on future flexibility requirements of Occitanie power system.

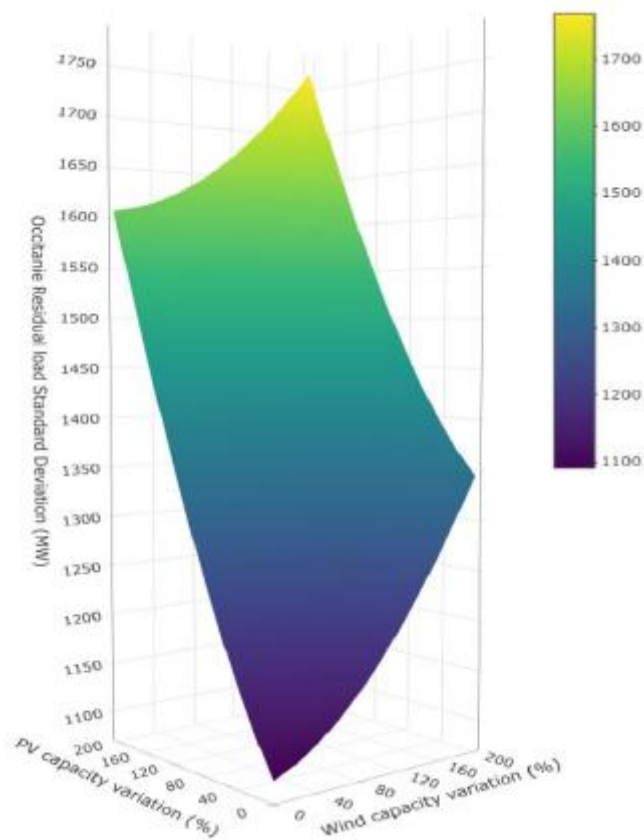


Figure 7 : Sensitivity of 2019 Occitanie Residual Load Standard Deviation to changes in Wind and solar PV generation capacities

Another intuitive result that is confirmed by this analysis is that an increase in PV capacities affects more the RL variability than an increase in wind capacities would do. Indeed, the day-night cycle associated with solar PV electricity production impacts a lot the standard deviation of our hourly Residual Load time-series. This fact can be clearly observed on Figure 8, where the surface appears steeper of the PV side than on the wind side. We can also note that the Occitanie RL Standard Deviation augments almost linearly with PV capacities, while it has a more convex shape on the wind capacities side. Again, this result is quite intuitive, as variability associated with PV capacities is dominated by the predictable and periodic day-night cycle, while wind variability is a much more complex phenomenon. Overall, this simple variance-based sensitivity analysis has shown that, with increasing VRE capacities, flexibility requirements assessment will eventually become not only a

more and more important task for grid operators, but also a critical source of uncertainty that might have significant impacts on electricity market participants.

## 5. Conclusion

In this paper, we have shown that forecasting power system flexibility requirements can be achieved with a low error by using a combination of time-series decomposition (i.e., CEEMDAN) and artificial neural network, namely ConvLSTM-2D. Using this methodology, the hourly Residual Load of French region Occitanie power system can be forecasted for an entire year with MAPE and RMSE scores of respectively 3.02% and 137.12 Megawatts (MW). In the future, we believe that such forecasting tools could be very useful for electricity market participants. Producers, retailers, prosumers and even grid operators could indeed perform a better unit commitment schedule, avoid grid congestions, and anticipate spikes on day-ahead markets. Having consistently accurate forecasts at different timescales could also help policy makers to design efficient and realistic energy policies.

From a methodological point of view, this work proposes a functional framework for forecasting flexibility requirements. Using this straightforward data-driven methodology, energy stakeholders can basically forecast load, VRE production and Residual load at any timescale and for any given geographical perimeter. Unlike most traditional deterministic simulation methods, the CEEMDAN-ConvLSTM-2D framework requires no prior knowledge of energy systems or Residual Load mechanics. Moreover, our methodology can be run on a personal laptop in reasonable times and can make use of real-time incoming data to enhance predictions, which is not the case for traditional econometric time-series forecasting methods.

Thus, we believe that this forecasting framework has a strong potential for a daily use, even for non-energy experts.

However, current technical limitations related to deep-learning models' training (i.e., computational resources available) still impose to select a rather small forecasting window size, in our case twenty-four hours. This means that our proposed framework can currently only forecast the next day of RL without having access to new data. While the model's error results remain stable as forecasting steps advance, it would still require expanding the forecasting window size to predict Residual Load tendencies further than twenty-four hours ahead. The very fast pace of developments in the Computational Intelligence field suggests that such limitations will soon to be overcome, allowing then actual long-term hourly forecasting with ANN-based models.

Nonetheless, if one intends to make use of such data-driven forecasting framework, he or she should keep in mind the “*Business-As-Usual*” nature of the provided forecasts. Indeed, the forecasts produced here with our CEEMDAN-ConvLSTM-2D model relies only on past observations. Therefore, future shocks on either electricity consumption or production such as a world pandemic or a rapid change in electricity markets regulation cannot be predicted at all since they do not appear in the past data used to train the model. Long-term prediction capabilities of the CEEMDAN-ConvLSTM-2D framework are yet in line with deterministic methods which neither can predict such events.

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To enhance the predictive performances of our proposed methodology, adding Residual load explanatory variables such as temperatures, economic activity, or heating and/or air-cooling equipment to the training data might very well help. Some future research avenues could be therefore focused on providing such explanatory data (in the form of time-series) for the model training and see if the forecasting results are enhanced. Additionally, combining expert's knowledge and our modeling framework could lead to the design of plausible scenarios for the future power systems. More generally, the CEEMDAN-ConvLSTM-2D methodology should be tested on other time-series data to assess its forecasting performances on other types of sequential phenomena.

On a final note, the variance-based sensitivity analysis conducted on Occitanie Residual Load suggests that planned increases in VRE capacities will growingly affect the RL variability. This expected development surely requires market design adjustments, enhanced grid management, both at the production and demand level, and overall, new tools for electricity market participants to assess the actual value of Variable and Renewable Energy sources.

At the end of the first chapter, we have delved deeply into the current dynamics and specific challenges of the Occitanie region in terms of variable renewable energy (VRE) production and energy management. The detailed analysis of the Residual Load has highlighted the inherent complexity of integrating VREs into the regional energy grid, underscoring the critical importance of effective flexibility management. Having established a solid understanding of the current flexibility needs and the challenges posed by VRE integration, it is now time to turn our attention to potential solutions and optimization strategies.

The second chapter opens with the development of our *Optimiflex* model, a tool designed to address these very challenges. Having already identified and quantified the flexibility needs of Occitanie's energy system, we will now explore how these needs can be optimally met. This chapter focuses on the development of flexibility management strategies, analyzing the various technologies and sources of flexibility available in the region. By integrating these elements into the *Optimiflex* model framework, we seek to determine how effective flexibility management can be achieved, balancing costs, efficiency, and sustainability







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# CHAPTER II

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## A REGIONAL POWER SYSTEM FLEXIBILITY MANAGEMENT MODEL AND ITS APPLICATION TO FRENCH REGION OCCITANIE

*Théotime Coudray*



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# SYNTHESE DU CHAPITRE 2

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## 1. Introduction

L'Agence Internationale de l'Énergie (AIE) recommande l'établissement de marchés locaux décentralisés pour atténuer la représentation non optimale des congestions de réseau inhérentes au marché de gros national. Les marchés locaux de flexibilité peuvent également réduire les coûts opérationnels des systèmes électriques, optimiser la planification des sources VRE locales et offrir de nouvelles opportunités économiques pour les participants au marché de l'électricité.

Plusieurs formulations de marchés de flexibilité ont été proposées, allant de modèles d'optimisation centralisés à des approches de théorie des jeux, en passant par des modèles basés sur des enchères et des modèles de simulation. Alors que de nombreux travaux analysent les mécanismes de marché de flexibilité à l'échelle des micro-réseaux ou de l'ensemble du réseau de distribution, l'échelle régionale est moins étudiée. De plus, les études sur la flexibilité ne couvrent pas explicitement les coûts réels de la gestion de la flexibilité.

Dans cet article, nous proposons un modèle d'optimisation des coûts pour la gestion de la flexibilité. On cherche à évaluer comment l'équilibre offre-demande se réalise à une échelle semi-horaire, en tenant compte de la production VRE, de la consommation d'électricité, des échanges interrégionaux et des sources locales de flexibilité. Nous introduisons ainsi un modèle de gestion de la flexibilité basé sur l'ordre de mérite qui peut aider à identifier les sources de flexibilité les plus utilisées tout en estimant le coût total de la flexibilité. Une application du modèle à la région Occitanie illustre son fonctionnement et les résultats attendus dans le cadre d'une situation *Business-as-Usual*.

## 2. Méthodologie

La section méthodologie de ce deuxième article sur la gestion de la flexibilité des systèmes électriques régionaux aborde deux aspects clés. D'abord, elle réintroduit le concept de RL pour estimer les besoins en flexibilité d'un système énergétique. La RL est calculée en soustrayant la production d'énergies renouvelables variables, comme l'énergie solaire PV et éolienne, de la demande totale d'électricité. Cette méthode est appliquée à des séries temporelles pour observer l'évolution des besoins en flexibilité. Ensuite, le modèle inclut les échanges d'électricité inter-régionaux dans le calcul de la RL pour fournir une estimation précise des besoins en flexibilité d'un système régional, où sont cette fois-ci soustraits les flux d'énergies provenant de régions adjacentes.

Le deuxième aspect majeur de la méthodologie est le développement du modèle d'optimisation *Optimiflex*. Ce modèle combine la planification centralisée et les aspects de marché pour gérer la flexibilité. Au cœur d'*Optimiflex* se trouve l'organisation des

technologies de flexibilité en un ordre de mérite, basé sur leurs coûts et capacités respectifs. Cette méthode permet une allocation efficace des ressources, en veillant à ce que les options les plus économiques soient utilisées en premier, maximisant ainsi l'efficacité et minimisant les coûts globaux du système. Les technologies prises en compte comprennent un éventail diversifié de sources de production contrôlable et de stockage d'énergie, telles que les centrales thermiques alimentées par des biocarburants, les centrales à cycle combiné au gaz (CCGT), les centrales nucléaires, ainsi que des solutions de stockage comme les stations de transfert d'énergie par pompage (STEP) et les batteries stationnaires. Le regroupement de ces technologies dans des centrales virtuelles (VPP) est une approche qui facilite la gestion et l'optimisation de ces ressources diverses. Le modèle inclut des contraintes techniques telles que la capacité maximale des technologies et l'état de charge des systèmes de stockage. Il est ensuite résolu par programmation linéaire en utilisant le package Python PuLP, permettant ainsi une analyse détaillée des résultats de simulation pour la demande de flexibilité projetée pour l'année 2050, tâche que l'on réservera pour le dernier chapitre.

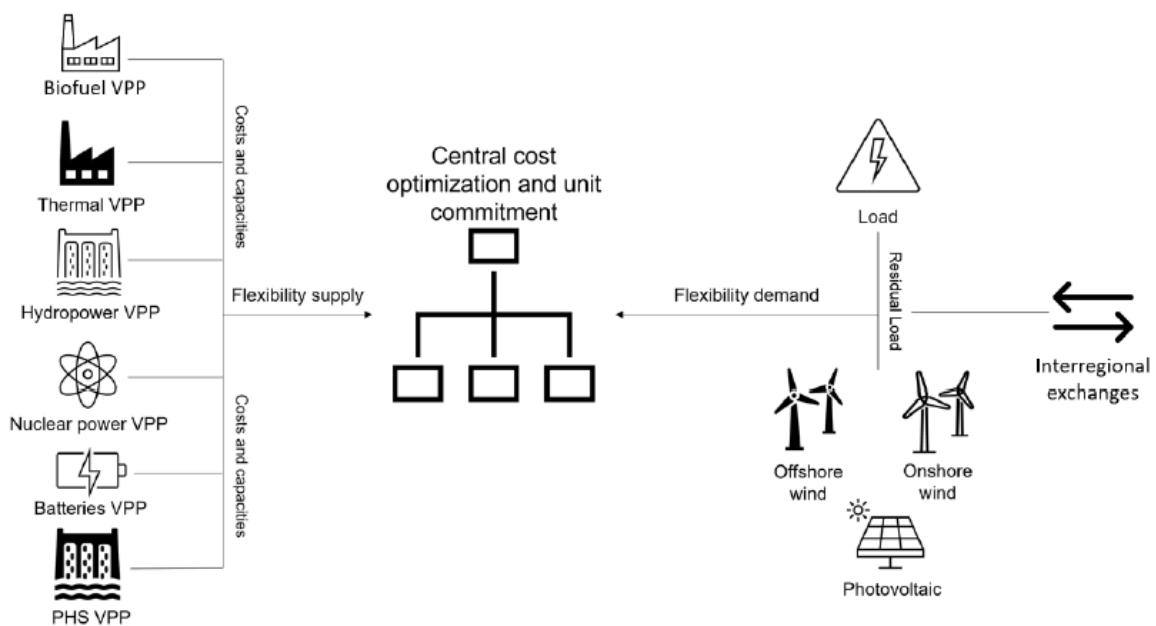


Figure 10 : Représentation schématique du modèle *Optimiflex*

### 3. Application à la région Occitanie : cas BAU

Ici, le chapitre se concentre sur l'utilisation pratique du modèle *Optimiflex* dans un scénario de référence (BAU) pour la région Occitanie pour l'année 2021. L'objectif est d'identifier l'engagement optimal des unités de flexibilité à chaque demi-heure de l'année et de calculer le coût total de la gestion de la flexibilité pour cette région. Ce test vise à comprendre comment les besoins en flexibilité pourraient être gérés en utilisant les capacités et les coûts des unités locales flexibles.

La section débute par la paramétrisation du modèle, intégrant les données sur la RL de la région Occitanie, qui inclut la consommation, la production des VRE et les échanges interrégionaux. Les coûts et les capacités des éléments de l'offre de flexibilité sont définis en utilisant des données réelles et une analyse approfondie de la littérature sur les coûts de l'électricité. Les différentes technologies de flexibilité sont classées en fonction de leur coût marginal et de leur capacité pour établir un scénario de base pour Occitanie en 2021.

Le modèle est ensuite utilisé pour déterminer l'ordre optimal des fournisseurs de flexibilité. Les résultats indiquent que les sources traditionnelles de flexibilité comme le nucléaire et l'hydroélectricité sont principalement utilisées pour répondre à la RL positive. Il est également observé que certaines technologies de flexibilité positive plus coûteuses, telles que les turbines à combustion et les batteries, ne sont pas nécessaires dans ce scénario. Les

courbes de charge pour différentes sources de flexibilité montrent des modèles saisonniers et la prédominance de certaines technologies en fonction de la demande et des coûts.

Enfin, le modèle, résolu par programmation linéaire avec Python PuLP, confirme l'équilibre du système énergétique pour Occitanie en 2021. L'analyse des coûts associés à la fourniture de flexibilité révèle un motif saisonnier en lien avec la RL. Ces coûts sont principalement influencés par la demande de flexibilité et les coûts marginaux des sources de flexibilité. Le coût total de fourniture de flexibilité pour l'année s'élève à environ 1,335 milliard d'euros, ce qui représente l'équivalent des dépenses nationales de RTE la même année.

En conclusion, cette section illustre comment le modèle Optimiflex peut être appliqué de manière pratique pour gérer efficacement les besoins en flexibilité d'un système énergétique régional, tout en fournissant une estimation claire des coûts associés à cette gestion.

## 4. Discussion et conclusion

A la fin de l'article, nous explorons les implications de notre modèle d'optimisation des coûts, *Optimiflex*, appliqué au scénario standard de la région Occitanie en 2021. Le modèle vise à éclairer les aspects du problème de fourniture de flexibilité dans un système énergétique dominé par la production VRE. Notre objectif est de relier deux échelles différentes : le réseau national avec ses infrastructures coûteuses, et les sources locales de production d'électricité et de flexibilité. Nous soulignons que la production de VRE et



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l'utilisation de sources locales de flexibilité sont plus rentables et permettent une meilleure gestion de la congestion au niveau du système de distribution.

Notre étude met en évidence que l'utilisation de sources locales de flexibilité pourrait être plus efficace en termes de coûts et favoriserait une meilleure gestion des congestions au niveau du système de distribution. Les résultats obtenus avec ce cadre de modélisation permettent d'analyser les investissements nécessaires pour des périodes futures, grâce à la fonction de coût marginal estimée qui indique le prix attendu pour une année complète de fonctionnement. Cette approche permet d'effectuer des calculs de valeur actuelle nette pour évaluer les investissements futurs.

En outre, le cadre de modélisation proposé est vu comme un terrain d'essai pour explorer divers scénarios ou trajectoires de transition énergétique. Nous cherchons à fournir un outil simple, basé sur l'ordre de mérite, capable de résoudre la gestion de la flexibilité d'un système énergétique donné à une échelle temporelle précise. Bien que notre modèle inclue quelques contraintes techniques, il révèle de nombreux aperçus intéressants sur les coûts et les technologies à considérer pour soutenir l'intégration des sources VRE dans les systèmes énergétiques. Notre méthodologie couvre à la fois les besoins en flexibilité et les aspects de gestion de la flexibilité, permettant aux économistes de l'énergie de représenter un large éventail de scénarios possibles de transition énergétique incluant le développement des sources VRE.

Notre conclusion souligne que le modèle démontre une forte dépendance d'un système énergétique régional renouvelable sur les capacités de suivi de charge du nucléaire, tout en

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montrant que l'atteinte d'un mix de production flexible et décarboné est réalisable, du moins à l'échelle de la région Occitanie. Notre modèle indique également que des bénéfices positifs pourraient être réalisés sur un marché local de la flexibilité, encourageant ainsi les investissements dans les capacités flexibles à l'échelle régionale. Les travaux futurs devraient explorer comment d'autres formes de besoins en flexibilité pourraient affecter le prix auquel la demande de flexibilité est servie. Notre méthodologie proposée est destinée à être utilisée pour explorer des voies potentielles de transition énergétique, telles que l'inclusion de véhicules électriques à batterie dans le modèle de consommation, ou la réduction de la consommation d'électricité dans le secteur du bâtiment, et pour étudier de nouveaux types de capacités de flexibilité comme le Power-to-X ou le Vehicle-to-Grid



# A REGIONAL POWER SYSTEM FLEXIBILITY MANAGEMENT MODEL AND ITS APPLICATION TO FRENCH REGION OCCITANIE

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## 1. Introduction

The development of Variable and Renewable Energy (VRE) sources is a key component of policies aiming at decarbonizing the electricity sector. In France, solar photovoltaics (PV) and wind power capacities have been increasing rapidly since the 2010 decade, notably because of pro-active subsidy mechanisms. To continue this trend, the French government has issued an energy planification policy [MTES, 2019] in 2019 that sets the targets of VRE penetration at the national scale for the 2019-2023 period. As VRE are mostly decentralized electricity generation technologies, the energy planification document also include regional aspects that come to precise decarbonization and VRE development targets at the regional level.

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However, these planification strategies barely evoke the power system flexibility needed to achieve the inclusion of VRE within the electricity generation mix. Indeed, as VRE electricity production is uncertain, uncontrollable, and variable, the rest of the power system requires to be flexible, meaning that it can cope with rapid changes either in load or generation [Heggarty et al., 2019]. Power system flexibility is a flourishing field of energy science, but it is often left aside within energy policies although being crucial for future power system that include large shares of VRE. Achieving power system flexibility is a complex question that mobilizes many tools, from electricity storage to demand-side management, including investments in grid interconnexions and the creation of new types of electricity markets that enable the trading of flexibility products. The last are commonly cited as necessary tools to enable the penetration of VRE within power systems, since classical day-ahead wholesale markets were initially designed to accommodate controllable, fossil-fueled electricity generation. Specifically, the International Energy Agency (IEA) recommends the establishment of local, decentralized electricity markets to mitigate the non-optimal representation of grid congestions inherent to the national day-ahead wholesale market [IEA, 2016]. Besides enabling a better congestion management [Essmat et al., 2018], local flexibility markets can also be useful to tackle other challenges associated with future renewable based power systems [Jin et al., 2020]. Indeed, local flexibility markets are also reported to help reduce operational costs of power systems [Hon et al., 2018], to enable a more optimal scheduling of local VRE sources [Jin et al., 2016], and more generally to provide new economic opportunities for electricity markets participants [Thomas et al., 2019].

Several market formulations for flexibility markets have been proposed, ranging from centralized optimization models of social welfare or cost minimization [Torbaghan et al., 2016, 2018 ; Olivella-Rosell, 2018 ; Heussen et al., 2013 ; Zhang et al., 2013], to game

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theoretic approaches [Paudel et al., 2019 ; Su et al., 2014 ; Lee et al., 2015], including auction-based models [Zaidi et al., 2018 ; Zhong et al., 2018] and simulation models [Ringler et al., 2016]. While many papers analyze the flexibility market mechanisms at the scale of microgrids or at the whole distribution grid level, the regional scale is less studied [Gazafroudi et al., 2021]. Moreover, flexibility studies do not explicitly cover the actual costs of flexibility management, which is an important aspect of the problem. Finally, to our knowledge, none of the mentioned research works propose to settle the flexibility management for a whole year, at a high-resolution timescale, and using real-world data. They rather introduce market mechanisms in a theoretical manner and solve them for particular periods of time, when not using entirely simulated cases.

Therefore, in this paper, we propose an operational cost optimization model for flexibility management. More precisely, we want to assess how flexibility management can be achieved at a half-hourly timescale, considering the VRE production, the electricity consumption, the interregional exchanges patterns, and the local sources of flexibility. We thus introduce a merit-order based flexibility management model that can help identify which are the most used sources of flexibility, while contributing to estimate the total cost of flexibility. We present an application of the model on French region Occitanie that come to illustrate how the model works and what kind of results can be expected. The rest of the paper is organized as follows: in section 2, we present how the demand for flexibility is built, and what are the inner workings of our proposed cost-minimization methodology and how it could be solved. Then, section 3 will detail the results obtained while taking the Occitanie Business-as -Usual (BAU) scenario assumptions, and finally section 4 will provide the reader with a conclusion and a set of possible other research avenues.

## 2. Methodology

### A. Building the flexibility demand

The very first step needed to build a flexibility management model is to find a way to approximate the flexibility requirements of a given power system. As reported in [Kondziella et al., 2016], the most common methodology to achieve this task is to use the Residual Load (RL) function as a proxy for flexibility requirements, or put simply, the demand for flexibility. The RL concept can be described as the remaining electricity demand to cover once all electricity produced by VRE sources has been injected into the grid. In other words, the RL embodies the flexibility demand because it considers both the inelastic demand for electricity and the uncontrollable VRE generation. In simple terms, the RL function is the amount of electricity that must be covered by flexible means i.e., controllable generation, storage, demand-response, market exchange, or curtailment. In a context of scarce VRE generation, the RL will most probably be positive, meaning that more electricity must be produced to cover the entire electricity consumption. However, when VRE production is higher than the electricity demand, the RL happens to be negative, meaning that part of the VRE generation must be evacuated in some way. At time  $t$ , the Residual Load, or the Demand for Flexibility ( $RL_t^D$ ), is given by Equation (1) (where  $D$  is the total electricity demand,  $P^{PV}$  is the solar photovoltaic production,  $P^{TW}$  is the solar terrestrial wind production, and  $P^{OW}$  is the offshore wind production).

$$(1) \quad RL_t^D = D_t - (P_t^{PV} + P_t^{TW} + P_t^{OW})$$

We can apply this equation to time-series data to represent the evolution of the flexibility demand over time, thus uncovering patterns that will influence which will be the most suited flexible source to use. Another advantage of the RL concept is that it can be applied to power systems of various sizes, from multinational grids to local mini-grids, as long as they incorporate uncertain and variable generation. As an example, we provide in Figure 8 the RL of Occitanie power system in 2021, at half-hourly timescale. We can clearly identify strong seasonal patterns that are due to the seasonal nature of electricity consumption and VRE generation. The RL is also very variable, with a peak of variability during winter, when both wind generation and electricity consumption intensify.

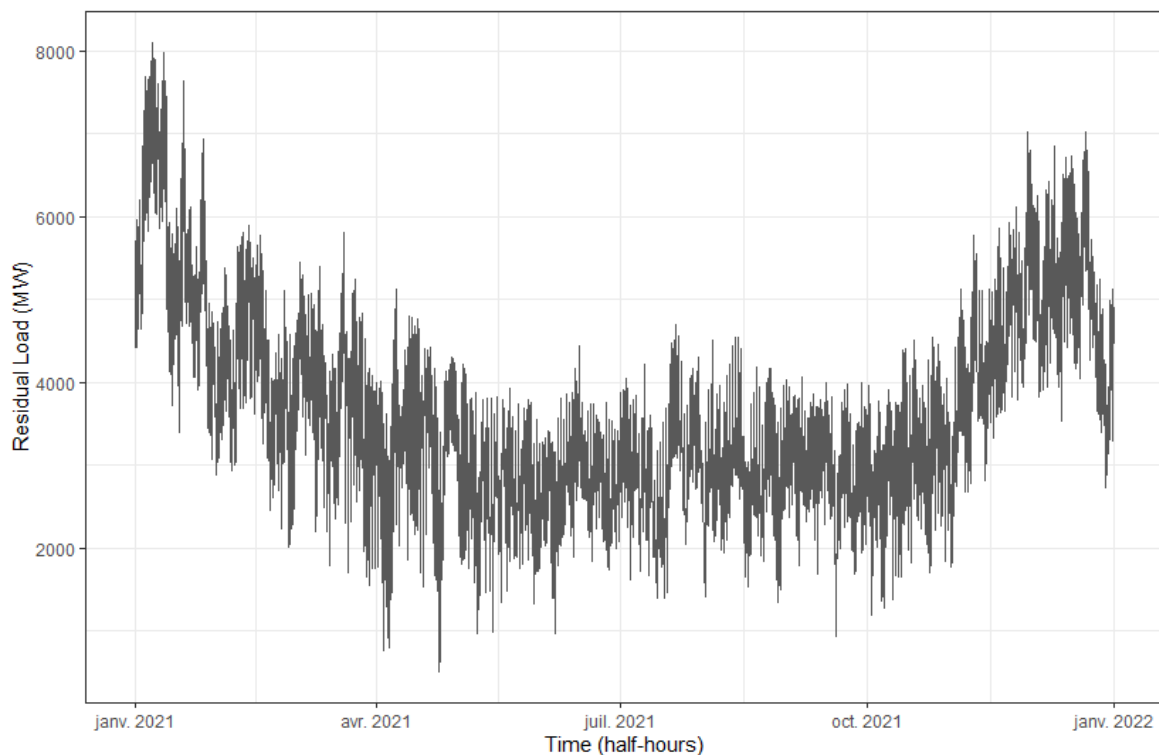


Figure 8 : Half-hourly Occitanie power system Residual Load in 2021

As our aim is to propose a regional version of flexibility analysis, we must consider the interregional exchanges of electricity that occur. Indeed, as there are no physical boundaries of the power system between a given region and another (since grids are designed



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nationally and even interconnected to other countries), one can consider that the balance of interregional exchanges in a given regional power system is an exogenous variable that does not respond to any price signal and thus cannot be optimized. Said in another way, as there are only national markets but no regional ones, it is compulsory to include the flows of electricity that transit between the observed regional power system and the others in the regional Residual Load function. This way, one can estimate the actual needs of flexibility that must be covered by local sources. Therefore, we propose an extension of the Equation (1) that include the balance of interregional electricity exchanges:

$$(2) \text{RLX}_t^D = \text{RL}_t^D + (X_t - I_t)$$

Where  $\text{RLX}_t^D$  is the Residual Load augmented with the balance of interregional exchanges ( $X_t - I_t$ ). In the case we are occupied with, Occitanie region is connected to Nouvelle-Aquitaine, Auvergne-Rhône-Alpes and Provence Alpes Côte d'Azur regions and interconnected to Spain. Unfortunately, we do not have access to more precise data about the exchanges occurring between Occitanie and these regions, the only time-series we have access to being the balance of all exchanges. This balance is most of the time negative, indicating the region Occitanie is most often importing electricity from neighboring regions. This result is expected as region Auvergne-Rhône-Alpes is well known for being a center of electricity production, with many of the French fleet of nuclear reactors being installed in this region. Figure 9 shows that when we incorporate the balance of interregional exchanges within the Residual Load function, it decreases the need for flexibility of the Occitanie power system to a point that it becomes negative for a certain period during the end of summer, when consumption is low and PV production high. Adding this variable to the RL function

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also causes this last to become much more variable, with a standard deviation that increases by around 200 MW compared to the original RL, see Table 5 for descriptive statistics of the Occitanie 2021 Residual Load and its dependent variables.

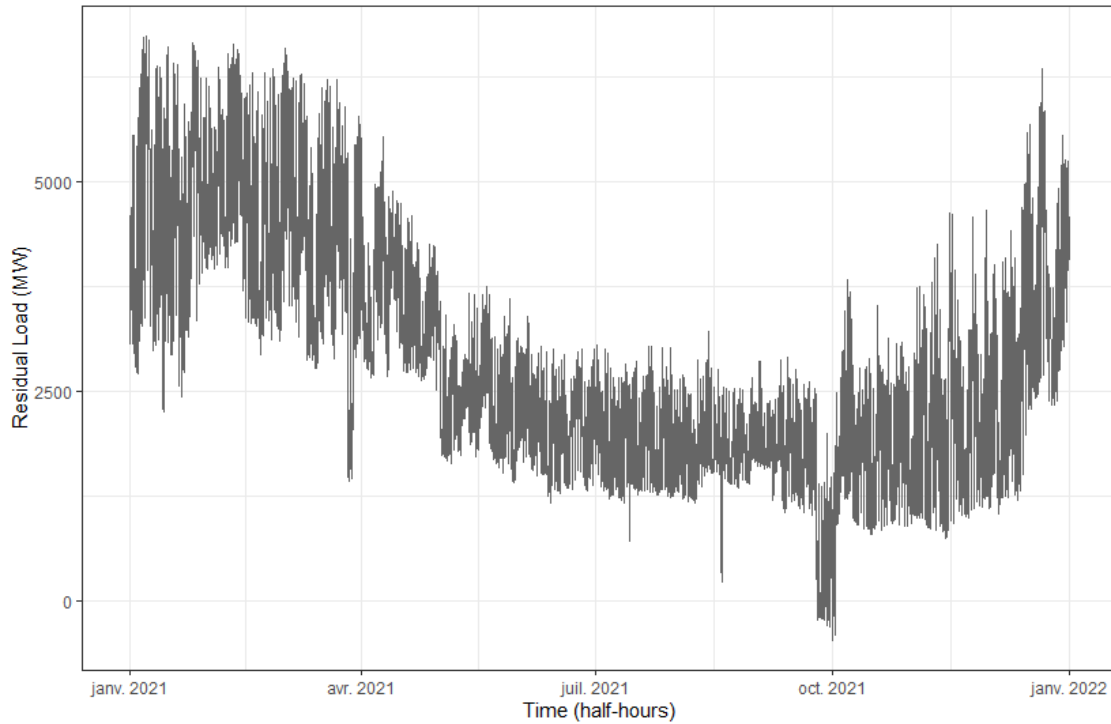


Figure 9 : Half-hourly Occitanie Residual Load including the balance of interregional exchanges for 2021

Time-Series	Datapoints	Min.	1 <sup>st</sup> Qu.	Median	Mean	3 <sup>rd</sup> Qu.	Max	Std. Dev.
Consumption	17 520	2 356	3 569	4 092	4 312	4 896	8 735	1 064.49
PV generation	17 520	0	0	5	339	612	1 828	489.77
Terrestrial wind generation	17 520	0	97	322	397	636	1 323	330.67
Residual Load	17 520	516	2 752	3 354	3 575	4 239	8 099	1 168.09
Balance of interregional exchanges	17 520	- 2 948	- 2	817	784	1 514	4 658	1 182.09
Residual Load with the balance of interregional exchanges	17 520	-471	1 753	2 442	2 790	3 691	6 741	1 364.46

Table 5 : Descriptive statistics of half-hourly Occitanie Electricity consumption, VRE generation, interregional exchanges, and Residual Loads for the year 2021 (in MW)

By doing this calculation, we have here provided an approximation of the flexibility requirements the Occitanie power system had in 2021, at a half-hourly timescale. We can clearly see on Figure 9 that the flexibility requirements have multi-temporal aspects, as the RL varies both within hours and days, but also between seasons. This indicates that the system requires flexibility sources that can both operate on short and longer timescales, either by ramping up or down their production, or by simply remain unutilized.

## B. *Optimiflex*: A linear optimization model for regional flexibility management

In standard economics, one expects a demand to be met with a supply, and this is precisely the topic we will address in this section, as we will introduce the characteristics of our flexibility management model named *Optimiflex*. We voluntarily use the term *management* model as our approach combines both traditional centralized cost optimization mechanics and market aspects that we will further describe in this section.

### i. Design for flexibility management: between market and centralized planning

The general form of our proposed approach is the following: given a demand for flexibility, flexibility providers are pooled together according to the technology they use to

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provide flexibility, and are called to serve the flexibility demand, following a cost-efficiency principle. A central planer, which could take the form of a market operator, collects the marginal costs and available capacities of every flexibility technology and orders them increasingly, in the form of a classical *merit-order*. Then, the central flexibility planer schedules flexibility capacities according to their rank in the merit-order, following a cost optimization procedure.

This choice of design is motivated by the common interest of all power system participants to serve the residual load, as a lack of flexibility could have dramatic consequences on both technical and economic aspects of power systems. As in [Heilmann et al., 2021], we indeed cast the problem of power system flexibility as a classical demand-supply matching issue. In a sense, we consider that there is such an urgent need for flexibility in renewable-based power system, that coordination must be ensured by an entity (the central planer) that has for sole mission to make sure that the flexibility is served, like a Transmission System Operator (TSO) is responsible for the frequency balancing. The difference between our central flexibility planer and a TSO is the scale at which they operate. If in general the TSO is responsible for the frequency balancing at the whole national grid scale, in our proposal, the aim is to make the best use of local VRE and flexibility sources, thus we propose that the central flexibility planer operates at the regional scale. In the literature, the general use case is to propose flexibility markets at the microgrid level, but the zonal or nodal scales have also been investigated, which makes sense as the flexibility issue is traditionally associated to the DSO being responsible of the congestions management [Zhang et al., 2013 ; Rosen et al., 2013]. Also, we consider that our proposal would simplify the collection of capacities and cost data, as aggregators of flexibility are mostly decentralized entities. The choice of a regional planification of flexibility sources which follows a cost-optimization

principle is thus proposed as a way to maximize the use of local and flexible Distributed Energy Resources (DER) in an efficient manner.

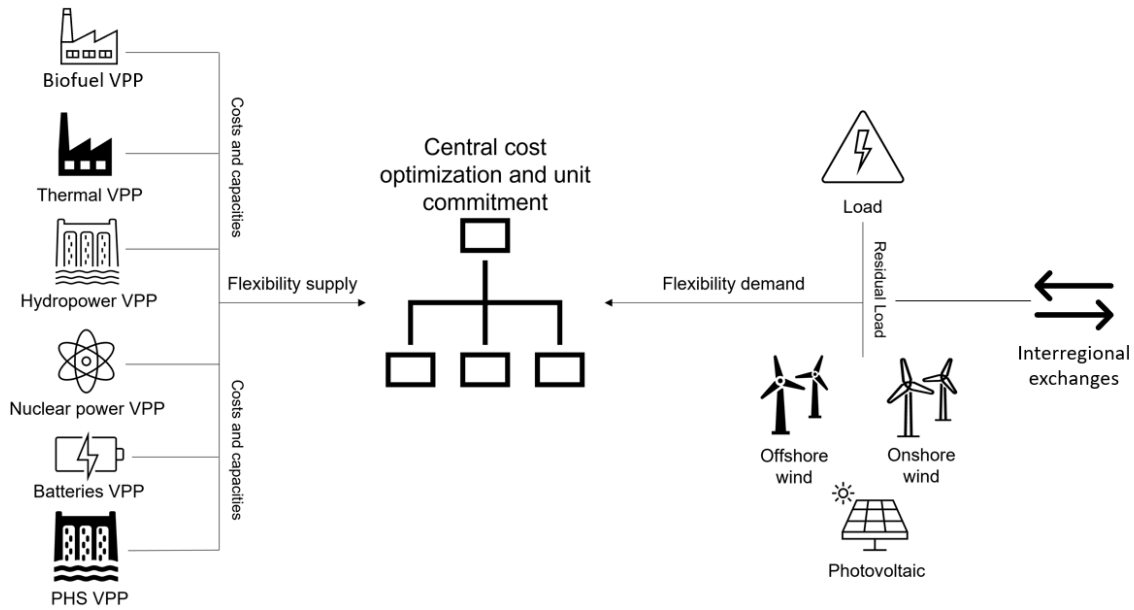
## ii. Flexibility suppliers

The last sub-section described how a party responsible for the flexibility management at the regional scale would operate. However, actual technologies, or mechanisms that provide flexibility to the system were not discussed. As mentioned before, the common characteristic of these flexibility providers is that they can operate in a controllable manner. Therefore, the first types of flexibility providers we can include to build our flexibility supply function are the mainstream controllable generation technologies actually used in Occitanie nowadays. These technologies include: bio-fueled thermal generation, Combined-Cycle Gas Turbines (CCGT), nuclear power, and hydraulic retention plants. These technologies have ramp rates that allow them to produce at full capacity within minutes (hydraulics) or tens of minutes (thermal generation). Even nuclear power has been proven to have interesting load following abilities and can therefore be included in flexibility supplying units that operate at the half-hourly timescale [Cany et al., 2016 ;Jenkins et al., 2018 ]. In our methodology, we propose that all units that use the same generation technology are grouped in dedicated Virtual Power Plants (VPP). From the point of view of the flexibility management operator, this helps to classifies the flexibility providing units into a merit-order.

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Besides conventional generation, the other type of flexibility providers is the one that make use of storage technology to provide flexibility to the system. Contrary to conventional generation, these units can either store excess electricity in a charging process or produce electricity while discharging. The reader will understand that in the case of negative RL, storage technologies are most needed to help absorb the excess renewable electricity produced. In our work, we chose to model the current existing storage technologies, which are Pumped Hydro Storage (PHS) and stationary batteries. Further work could include developing multisector storage technologies, like Vehicle-to-Grid or Power-to-Gas, but for now, we stick to the already existing ones. Here again, storage capacities are grouped into VPP according to their type (one VPP for PHS and one VPP for batteries), and VPP managers are responsible of the allocation of their own capacities once central optimization has been conducted.

Overall, the flexibility supply function that will serve the demand defined in the previous sub-section will be made of capacities offered by VPP that represent the conventional generation and storage technologies. As a summary, the diagram in Figure 10 lays out a visual representation of the *Optimiflex* model.

Figure 10 : The *Optimiflex* model overall design

### iii. Objective function and constraints

After having generally described the form of our flexibility supply function, we aim to provide in this section a more formal definition of the flexibility management problem by presenting the model's objective function and its constraints. The objective of the model is to minimize the total cost of providing flexibility to the system at each timestep, while ensuring that all demand for flexibility is served. Therefore, the objective function of the model can take the form introduced in Equation (3):

$$(1) \min CT_t = \sum_{i=0}^k q_t^i * c_i$$

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Where  $CT_t$  is the total cost of flexibility at time  $t$ ,  $q_t^i$  is the quantity of flexibility provided by technology  $i$  at time  $t$ , and  $c_i$  is the marginal cost of technology  $i$ .

As presented before, we emphasize that the flexibility demand must be served at any time  $t$  by introducing the constrained described in Equation (4), with  $RLX_t^D$  the flexibility demand and  $RL_t^S$  the flexibility supply at time  $t$ .

$$(2) \forall t \in T : RLX_t^D = RL_t^S$$

The rest of the model consists in technical constraints of the flexibility providing units. The first constraint is on capacities, i.e. each flexibility technology cannot offer more than its maximum capacity (see Equation (5)). In Equation (6), we precise that bidirectional flexibility units (i.e. storage technologies) have a minimum (or maximum negative) capacity.

$$(3) \forall i \in I \text{ and } \forall t \in T : 0 \leq q_t^i \leq q_{max}^i$$

$$(4) \forall b \in B \text{ and } \forall t \in T : q_{min}^b \leq q_t^b \leq q_{max}^b$$

With  $I$  the set of flexibility providing technologies, and  $B$ , a subset of  $I$ , the set of bidirectional flexibility technologies. In Equation (7), we describe how the set of storage technologies  $S$  is impacted by a constraint on the State of Charge (SOC), i.e., the fact that the amount of already stored electricity within the storage reservoirs limits the flexibility capacity these technologies can offer at time  $t$ .



$$(5) \forall s \in S \text{ and } \forall t \in T : SOC_{min}^s \leq SOC_t^s \leq SOC_{max}^s \text{ with } SOC_t^s = \frac{q_t^s}{q_{max}^s}$$

We also introduce a constraint on the decay of batteries-stored electricity. Equation (8) describes how batteries naturally discharge themselves at a rate of minus 5% of stored electricity per half-hour.

$$(6) \forall t \in T : SOC_{t+1}^{BAT} = 0.95 * SOC_t^{BAT}$$

Finally, we introduce a minimal capacity at which the nuclear VPP can operate. Indeed, the nuclear technology allows for a fast ramping of the production, but this last cannot be reduced down to a certain amount in order to avoid technical issues. Following the technical literature on the topic, we limit the ramping of nuclear VPP down to a minimum of 20% of their capacity.

$$(7) q_{min}^{nuc} \geq 0.2 * q_{max}^{nuc}$$

#### iv. Model solving

Overall, our proposed methodology can be summarized as a classical cost optimization program with constraints. Solving this model for each half-hour of the projected 2050 RL values can be achieved in various ways, from usual linear programming to the most advanced Reinforcement Learning techniques [Zhang et al., 2020 ; Yang et al., 2020]. As our focus is more to analyze the simulation results obtained than to provide a deep methodological

proposal, we opt for linear programming to solve the *Optimiflex* model. Precisely, we use the PuLP Python package as a toolkit to build, solve and analyze the outputs of our model.

### 3. Business-as-usual application

The *Optimiflex* model inner workings were presented in the previous section. We now propose to test our modeling framework with a baseline scenario. More precisely, we want to present the types of results that can be obtained with our methodology. By taking this test, we expect to identify the optimal commitment of Occitanie flexibility units for all the half-hours of the year 2021. Last but not least, our aim is also to quantify the total cost of flexibility management for the region Occitanie if our proposed market-design would be used. In simple terms, in this section is analyzed how the flexibility requirements could be managed if the capacities and costs of local flexible units would be used as a basis. This first application would therefore be referenced as the baseline flexibility management scenario and can be then compared to other scenarios of electricity consumption, VRE integration or flexibility deployment.

#### A. Parametrization

Section 2.1 already depicted the RL of Occitanie power system when it integrates the consumption, VRE generation and interregional exchanges variables. We thus already estimated the half-hourly flexibility demand values that will be used to test our flexibility management model. However, the capacities and marginal costs of the elements constituting the flexibility supply require to be parametrized for the model to be solved. As indicated

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above, we want to test our model with the current characteristics of the Occitanie power system.

Therefore, current values of costs and installed capacities are used to parametrize the Occitanie flexibility supply function. The costs are obtained with a rigorous survey of the electricity costs literature [IEA, 2020 ; IRENA, 2020 ; Kost et al., 2021] while installed capacities are directly taken from real-world data accessible on the *Open Data Réseaux Energies* platform. Table 6 references the marginal costs and capacities of flexible means the Occitanie region has as of 2021.

We want to precise that the terms *positive flexibility* refers to the technology capacity to produce electricity while needed when *negative flexibility* refers to the technology's potential to evacuate or store excess electricity.

Technology	Marginal Cost (€/MWh)	Positive flexibility capacity (MW)	Negative flexibility capacity (MW)
Stationary batteries	350	2	-2
Biofuel turbine	75	162	0
CCGT	65	157	0
Pumped Hydro Storage	77	1 500	-1 500
Nuclear power	28	2 620	0
Hydropower	25	2 337	0
Oil-fired turbine	115	152	0

Table 6 : Costs and capacities parameters of the flexibility suppliers in the Business-As-Usual Occitanie 2021

scenario

## B. Unit commitment

The first results we will present in this section relate to the shape of the optimal dispatch of flexibility units. To illustrate how the various flexibility suppliers are ranked into a merit-order that constitute the core optimization problem, we propose in Figure 11. a chart representing the merit-order obtained when the model is parametrized with the *Business-as-Usual* values.

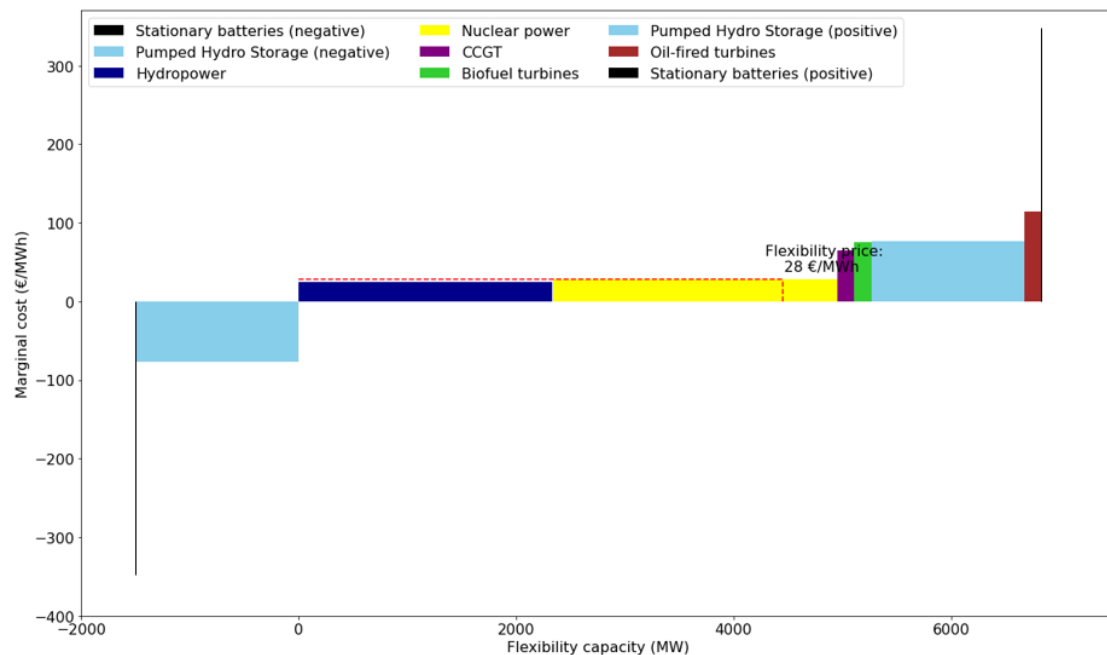


Figure 11 : Business-as-Usual flexibility merit-order when the flexibility demand is set at 4 454 MW (January 1st 2021 at 00:30 am)

This figure already tells us that traditional flexibility sources such as nuclear power and hydropower will primarily be used to serve the Occitanie RL when it is positive. However, in our experiment, the estimated RL for 2021 is negative during a small amount of time (see Figure 9 and Table 5), meaning that the bidirectional flexibility that will be used primarily will be the Pumped Hydro Storage in this case. In general, our merit order represents a classical supply function for the case of France, in which baseload demand is

covered with hydropower and nuclear, and peak load being covered by gas and oil-fired turbines. The capacities of battery storage technology are in 2021 so small that we expect this technology to contribute very low to serve the flexibility requirements.

### i. Solving the model

This first intuition is confirmed when, using the Python PuLP linear solver, we run the model for the 17 520 periods of the estimated Occitanie 2021 RL. The cumulative sum of flexibility capacities, either in positive or negative flexibility, is sufficient to serve the RL all the time, as our model ends up running with only optimal solutions to the optimization problem. This baseline result represents a first confirmation that our model accurately replicates the balance of the Occitanie power system for the year 2021. Note that another advantage of this simple model is that it can run this full year of half-hourly RL in about 8 minutes of computing time. This means that our proposed methodology can be suited to run many simulations of various combinations of load, VRE generation and flexibility capacities, rendering it particularly useful in the context of scenario analysis. In the next section, we present the other types of results that can emerge from our modeling, still using the Occitanie Business as Usual scenario values as an example.

### ii. Load curves

Firstly, and as expected, the load profiles of the various flexibility sources are all very different. As presented in Figure 12, the flexibility means that are the most used are logically the ones that are best ranked in the flexibility merit-order presented above. This means that when the flexibility demand is positive, the hydropower and nuclear power technologies will

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be activated to serve the amount of electricity that is lacking to cover the demand. This result is very intuitive, as these two technologies have the lowest marginal costs.

What is more interesting is that more expensive positive flexibility technologies are never called in this application. Neither oil-fired turbines nor batterie storage are needed to serve the flexibility demand. Figure 5 also depicts a typical seasonal pattern, as the production of flexible means decreases drastically in summer, when PV generation is at its maximum. Logically, in winter, cost-intensive technologies such as CCGT or biofuel turbines are called to help the system to cover peak-load.

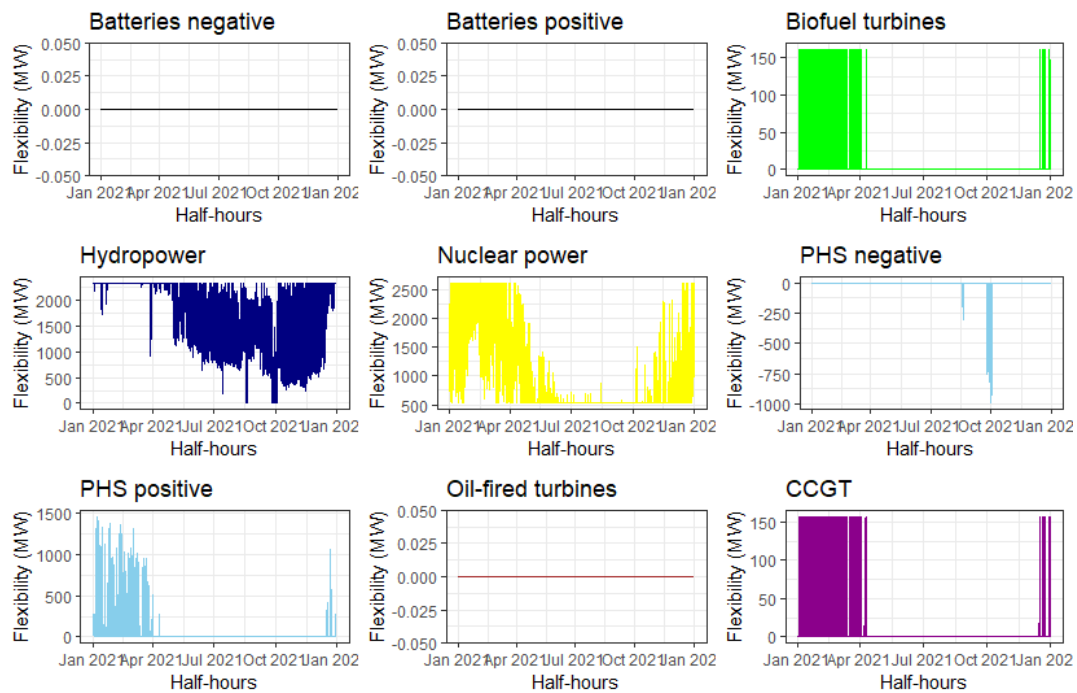


Figure 12 : Output load curves of the *Optimiflex* model when calibrated with the Business-As-Usual Occitanie 2021 scenario

To provide the reader with more insights, we propose in Figure 6 a chart displaying how often each flexibility mean is used when the *Optimiflex* model is calibrated with the Business-As-Usual Occitanie 2021 scenario. We can here again clearly see that the flexibility technologies that are the most used are the usual ones, i.e., nuclear power and hydropower. These results are important as they underline the fact that providing flexibility to the system

remains mostly inexpensive and decarbonated in 2021. More precisely, we can see here that the role of these usual baseload generation technologies could actually evolve into means to support the inclusion of VRE sources in the power system. Indeed, even if the nuclear VPP is calibrated to function at least at 20% of its maximal capacity, its production can be ramped up or down at a rate of 1 to 5% per minute, allowing it to be put in a *load following* mode that is used to serve the flexibility demand. The same occurs for the hydropower which can also ramp up or down its production very quickly. At the end, Figure 13 approximates the usual load curves of the French power system, another proof that our model is correctly calibrated to replicate these expected results.

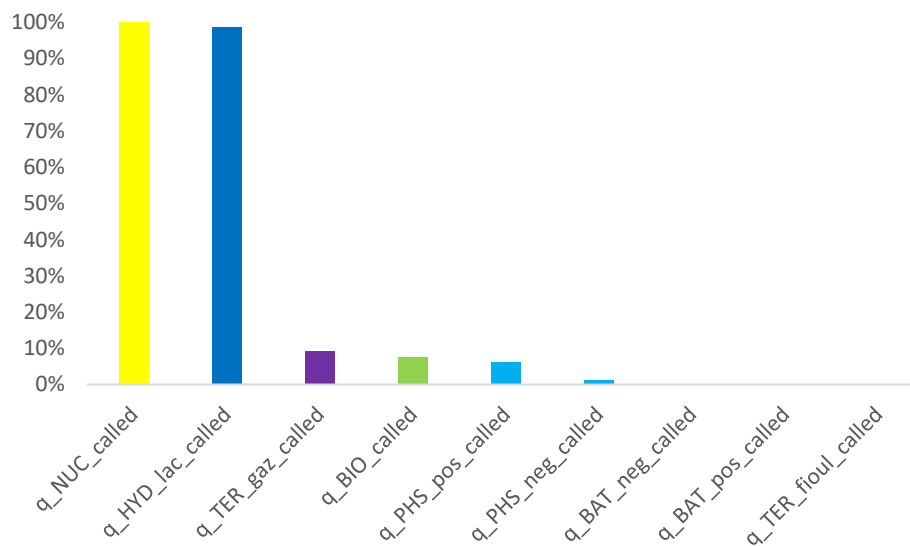


Figure 13 : Percentages of time each flexibility means is being called in the Business-As-Usual Occitanie 2021 scenario

### C. Cost of flexibility

After discussing the unit commitment realized when the *Optimiflex* model is calibrated with the business-as-usual Occitanie 2021 scenario values, we now focus on the costs associated with providing flexibility to the Occitanie power system. As the merit-order logic dominates our modeling framework, it is expected that the total cost is a function of the

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flexibility demand level and the marginal costs passed as inputs. In Figure 14, we present the half-hourly cost of matching flexibility supply and demand in our Business-As-Usual scenario. Associated descriptive statistics are provided in Table 7, as well as descriptive statistics of the half-hourly marginal price obtained for each solved period of the simulated year 2021.

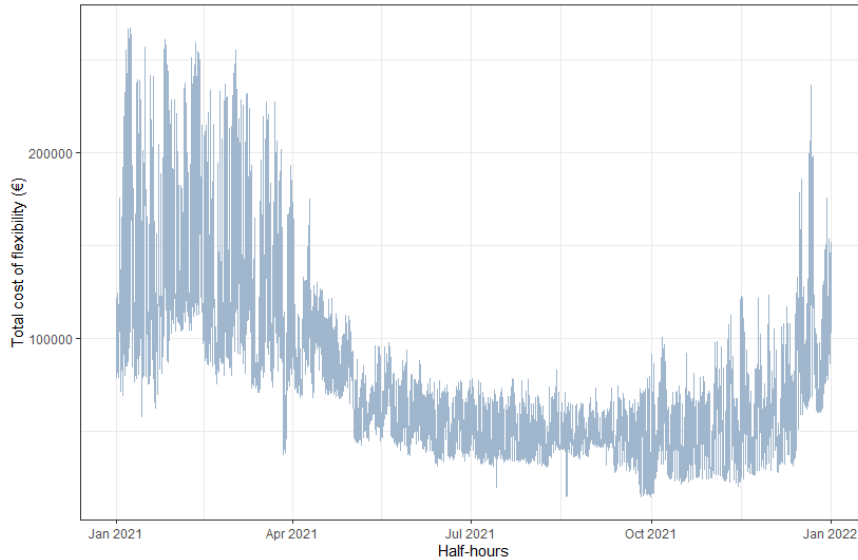


Figure 14 : Half-hourly total cost of flexibility in the Business-As-Usual Occitanie 2021 scenario

Time-series	Datapoints	Min.	1 <sup>st</sup> Qu.	Median	Mean	3 <sup>rd</sup> Qu.	Max	Std. Dev
Total Cost	17 520	14 747	45 847	62 997	76 207	96 344	266 945	42 899.19
Marginal price	17 520	-77	25	28	30.15	28	77	16.72

Table 7 : Descriptive statistics of the half-hourly total cost and marginal price of matching flexibility demand and supply in the Occitanie 2021 scenario

In a first look, we can see that the half-hourly total presents a strong seasonal pattern, and generally looks very much like the RL curve we presented in Figure 9. This confirms our intuition that the total cost is a function of the RL and the costs associated with each flexibility source. A closer look at the descriptive statistics let us infer more details about the costs of providing flexibility in this scenario. First, we can see that the total cost is never



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negative, even when the marginal technology is the negative Pumped Hydro Storage. This is due to the fact that to represent well the cost of providing storage with this technology, we introduced a negative sign relative to the negative flexibility it brings to the system. Second, the median marginal price is the one of the nuclear technology, which appears to be logical because of the constraint on production this specific technology has. In other terms, since the nuclear VPP is called 100% of the time, it feels intuitive that its marginal cost will also be the marginal price for a significant share of the time.

To summarize, the cumulated total cost of providing flexibility to the Occitanie power system under the Occitanie 2021 scenario assumption reaches precisely 1 335 140 400 euros per year. This amount seems significant, but at the same time it is in line with the 1 736 million euros spent in 2021, although at the national level, by the French Transmission System Operator. On average, the flexibility mean that is marginal most of the time is the nuclear power, as it must function all of the time by constraint, but also because it is one of the most cost-efficient technology in our modeled merit-order.

### D. Discussion

Although being not too sophisticated, our modeling framework and the Business-As-Usual scenario we tested with it can shed a light on various aspects of the problem of providing flexibility in a power system dominated by intermittent VRE electricity generation. First, our aim is to propose here a modeling framework that comes to link two very different scales: the national grid, with its large and costly infrastructures, and the local, distributed sources of both electricity production and system flexibility. Once again, it is expected that the production of VRE and the use of local sources of flexibility are more cost-efficient and

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can allow for a better congestion management at the scale of the distribution system. Moreover, the kind of results we obtain with our modelling framework allows for an analysis of the investments the system has to make for future periods of time. Indeed, by resulting in an estimated marginal cost function (represented in Figure 15.), our model shows what price can be expected for a full year of functioning, thus allowing for Net Present Value types of calculations.

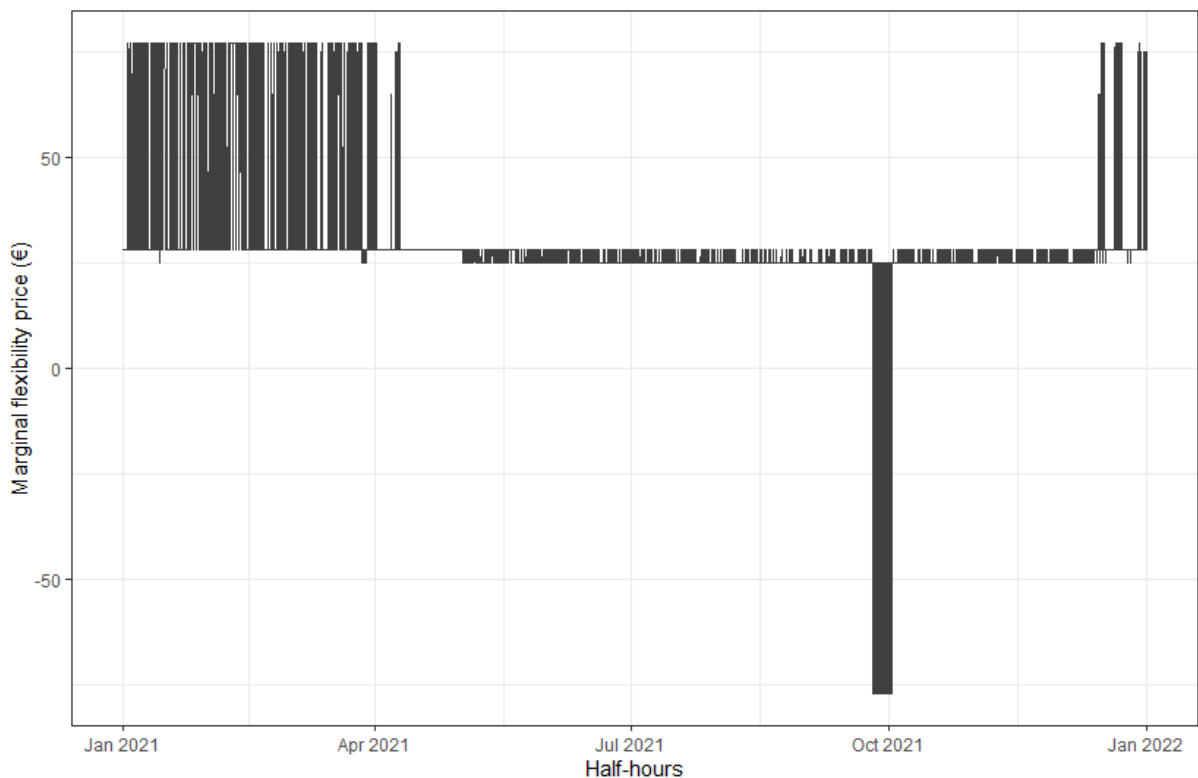


Figure 15 : Marginal cost function associated with the Occitanie 2021 Business-as-Usual scenario

Finally, we want to mention that the proposed modeling framework is in many ways a testbed to explore various scenarios or trajectories of energy transition. Our aim is to provide a simple, merit-order based tool that can solve the flexibility management of a given power system at a high-resolution timescale. Though few technical constraints have been added to the modeling framework, we think that from an energy economist point of view, it unveils

many interesting insights about the costs and technologies to consider to support the integration of VRE sources into power systems. From the creation of Residual Load time-series to the analysis of the hourly total cost of the flexibility management, our methodology covers both flexibility requirements and flexibility management aspects, allowing energy economists to represent a vast set of possible energy transition scenarios that include the development of VRE sources within a given territory.

## 4. Conclusion and research avenues

In this paper, we have investigated the use of a cost-optimization model to produce insights about the flexibility management the increasing shares of VRE induce for the Occitanie power system. In a first part, we have proposed a way to estimate the half-hourly flexibility requirements the region Occitanie had in 2021. Integrating both VRE generation and interregional exchanges time-series, our Residual Load function approximates well the flexibility requirements of the system, on a half-hourly basis. We have justified the incorporation of interregional exchanges by mentioning the fact that they do not respond to a price signal, and can thus be considered as fatal production, like VRE generation.

Most of the time, our Residual Load is positive, and follow a strong seasonal pattern. This means that the baseline technologies that are hydropower and nuclear power need to produce most of the time, but they also require to ramp up or down their production in order to follow the load variations. For a significant amount of time, other flexible units such as CCGT and Biofuel turbines must be called also to cover the peak load.

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Overall, it appears that the flexible mean that is used most of the time is the nuclear power. This result demonstrates the reliance a regional renewable-based power system would have on the nuclear load following capabilities. It also demonstrates that reaching a flexible and decarbonated generation mix is achievable, at least at the scale of the Occitanie region. Note that other region that do not benefit from large hydropower capacities should rely much more on carbonated flexible sources.

On another side, the shape of the marginal cost function that our model results in demonstrates that positive benefits can be made on a local flexibility market. This should encourage investments in flexible capacities at the scale of the region. Further work should explore how other shapes flexibility requirements could affect the at price at which flexibility demand is served.

It is actually the very purpose of the proposed methodology to be used to explore potential energy transition pathways. More precisely, we expect this modeling framework to be used to test other assumptions on Residual Load dynamics, for instance the inclusion of Battery Electric Vehicles (BEV) into the consumption pattern, or the reduction of the electricity consumption of the building sector. We also hope to see this modeling framework used to study new kinds of flexibility capacities, like Power-to-X (P2X) or Vehicle-to-Grid (V2G), as well as provide insights about the cost trajectory of a regional flexibility management when technological changes affect the way flexibility capacities are deployed.

The previous chapter presented an in-depth exploration of the Optimiflex model, shedding light on the capabilities and costs of different flexibility technologies in the context of the Occitanie region. We have seen how flexibility management can be optimized using a merit-order based approach, enabling efficient allocation of resources to meet flexibility

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requirements. These findings form a solid foundation to further our understanding of flexibility management and to consider future scenarios.

In the third chapter, we venture into the realm of scenario analysis, using the framework established by Optimiflex to explore various future scenarios for the Occitanie region. This chapter is dedicated to the analysis of alternative scenarios, examining how different consumption patterns, increased integration of VREs, and the evolution of flexibility technologies could impact flexibility management in the region. We will use the insights gained from the previous chapters to simulate and evaluate the impact of these scenarios, thus offering valuable perspectives on the potential trajectories of energy transition in the Occitanie region.





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# CHAPTER III

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The future of power system flexibility in Occitanie

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A scenario analysis

*Théotime Coudray, Sandrine Michel and Boris Solier*





# SYNTHESE DU CHAPITRE 3

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## 1. Introduction

Ce troisième chapitre se penche sur la transition vers des systèmes énergétiques bas carbone en réponse aux objectifs climatiques fixés par l'Europe et la France. L'Europe s'oriente vers une neutralité carbone d'ici 2050 avec des objectifs plus ambitieux pour 2030. En France, la Stratégie Nationale Bas Carbone (SNBC) et la Programmation Pluriannuelle de l'Énergie (PPE) définissent des cibles précises pour le secteur énergétique. La région Occitanie en France, profitant de conditions climatiques favorables, a élaboré un scénario de transition énergétique visant à atteindre un bilan énergétique positif grâce à l'augmentation des énergies renouvelables variables (VRE) : le scénario REPOS 2050.

Des scénarios variés de transition énergétique ont été développés par des entités telles que RTE, l'ADEME ou négaWatt, mettant en lumière la montée en puissance des VRE. L'intégration rapide de ces VRE dans le mix énergétique soulève des défis, notamment en termes de flexibilité des systèmes électriques, du fait de leur nature décentralisée et intermittente. Face à ces changements, les systèmes électriques historiquement centralisés doivent s'adapter, rendant pertinente une approche régionale.

Ce troisième chapitre propose donc d'analyser la flexibilité du système électrique de l'Occitanie à l'aide d'une modélisation par scénarios et d'un modèle d'optimisation linéaire. En

adoptant une perspective régionale, il vise à fournir une analyse fine adaptée aux particularités locales. Trois scénarios pour l'année 2050 sont développés, examinant comment gérer la flexibilité du système électrique face à une intégration élevée des VRE. Cette approche régionale est vue comme complémentaire à l'échelle nationale et vise à informer les politiques locales, tout en offrant des enseignements transférables à d'autres régions.

Le chapitre se structure autour de la construction des scénarios de RL pour 2050, de l'application de ces scénarios au modèle de gestion de la flexibilité et des analyses de sensibilité pour évaluer l'impact de différents paramètres sur le système électrique de l'Occitanie en 2050. Il conclut sur les résultats obtenus et propose des pistes de recherche futures dans ce domaine.

## 2. Méthodologie

Dans ce troisième chapitre, l'analyse de la gestion de la flexibilité du futur système électrique d'Occitanie commence par une approximation des besoins en flexibilité à l'aide de la fonction de RL. Cette fonction représente l'électricité à produire une fois l'énergie des sources variables injectée dans le réseau. La RL est un bon estimateur des besoins en flexibilité, car elle intègre la consommation inélastique et la génération incontrôlable des sources VRE. En Occitanie, la RL présente de forts motifs saisonniers, nécessitant une flexibilité positive en hiver et négative en été.

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Pour construire le scénario *Business-as-Usual* de la RL Occitane pour 2050, les données historiques de consommation électrique et les capacités des VRE de la région sont analysées. Les tendances observées entre 2006 et 2019 indiquent une consommation électrique relativement stable, bien que l'impact de la croissance économique sur la consommation future doit être pris en compte. L'intensité énergétique de l'économie d'Occitanie, dominée par les services et l'agriculture, est supposée diminuer, entraînant une demande énergétique totale de 198 TWh par an en 2050. En appliquant le pourcentage actuel de l'électricité dans la demande énergétique totale, la consommation électrique annuelle prévue est de 39,41 TWh, soit une augmentation de 22% par rapport à 2019.

Le scénario REPOS 2050, quant à lui, vise à faire d'Occitanie la première région française à bilan énergétique positif d'ici 2050. Ce plan ambitieux suppose une réduction de 39% de la consommation énergétique finale, dont 7% pour la consommation électrique, et ce principalement grâce à des efforts d'efficacité énergétique et une baisse de la consommation encouragée par des mesures politiques. L'électrification des véhicules et une augmentation significative des capacités des VRE sont également prévues. En conséquence, la CR dans ce scénario devient négative la plupart du temps, indiquant un surplus de production régional.

Le scénario d'*Électrification Intensive* explore une voie où l'augmentation de la consommation électrique due à une électrification massive n'est pas compensée par des efforts d'efficacité énergétique. Ce scénario prévoit une augmentation de 39% de la consommation électrique par rapport à 2019 et une exploitation importante des capacités VRE. La RL dans ce scénario est extrêmement variable et atteint des extrêmes plus intenses que dans les scénarios précédents, reflétant un besoin significatif de flexibilité négative et positive.

### 3. Application de référence

Dans cette section, nous explorons comment le mix de flexibilité actuel de la région Occitanie réagirait aux charges résiduelles prévues pour l'année 2050 dans trois scénarios distincts, en utilisant le modèle *Optimiflex*.

Nous débutons par paramétrer le modèle avec les coûts et capacités actuels des différentes technologies de flexibilité disponibles en Occitanie, que nous appelons la paramétrisation de référence. Ces technologies comprennent les barrages hydrauliques, les réacteurs nucléaires, les centrales à biocarburants, les centrales au gaz et au pétrole pour la flexibilité positive, et les stations de stockage par pompage hydraulique (PHS) et les batteries stationnaires pour la flexibilité négative. Nous incluons aussi l'échange sur le marché comme moyen de vendre ou d'acheter de l'électricité en excès ou manquante. Nous soulignons que les technologies de stockage comme les PHS réduisent le besoin en flexibilité négative.

En utilisant ces paramètres, nous créons un ordre de mérite, illustrant le coût marginal et les capacités de chaque technologie. Nous observons que dans un cas typique de forte demande en hiver, les réacteurs nucléaires deviennent la technologie marginale.

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Nous testons ensuite le modèle sur les scénarios 2050, découvrant que le mix actuel de flexibilité en Occitanie suffit à servir l'entièreté de la RL dans le scénario *Business-as-Usual*. Cependant, pour les scénarios REPOS 2050 et *Électrification Intensive*, environ 20% des périodes nécessitent des capacités de flexibilité au-delà de ce qui est disponible localement, indiquant un besoin d'investissement dans de nouvelles capacités de flexibilité, notamment pour le stockage ou le renforcement du réseau.

Les courbes de charge pour chaque technologie de flexibilité révèlent que les barrages hydrauliques, les réacteurs nucléaires et les échanges sur le marché sont les technologies les plus utilisées dans tous les scénarios. Le scénario REPOS 2050 dépend fortement de l'échange sur le marché pour gérer l'excès d'électricité renouvelable, tandis que dans le scénario d'*Électrification Intensive*, les réacteurs nucléaires et les échanges sur le marché sont encore plus sollicités pour répondre à la forte demande et à la production renouvelable.

Enfin, nous examinons les coûts totaux de flexibilité pour chaque scénario. Le scénario d'*Électrification Intensive* présente le coût moyen total le plus bas et la moindre volatilité, tandis que le scénario REPOS 2050 a le coût moyen le plus élevé et la plus grande volatilité. Nous notons que les résultats pourraient différer si les périodes avec des solutions non-optimales étaient incluses, mais nous choisissons de nous concentrer sur la capacité régionale de gérer nos propres besoins en flexibilité.

## 4. Analyses de sensibilité

Dans cette section de la thèse, nous réalisons des analyses de sensibilité sur quatre technologies clés de flexibilité pour le futur système énergétique de la région Occitanie : les réacteurs nucléaires, les barrages hydrauliques, les batteries stationnaires et les centrales à combustibles fossiles. Ces analyses sont essentielles car les capacités et coûts marginaux de ces technologies sont susceptibles de changer dans les prochaines décennies.

Pour les réacteurs nucléaires, nous examinons un scénario où ces derniers sont retirés du mix de flexibilité, compte tenu de leur vieillissement. Nous observons que le système peut encore répondre aux augmentations régulières de consommation d'électricité et de capacités renouvelables intermittentes, malgré quelques périodes où le mix de flexibilité ne suffit pas.

Concernant l'hydraulique de haute chute, nous explorons l'impact du changement climatique sur la disponibilité de cette technologie en réduisant de 10 % sa capacité. Les résultats montrent que cette réduction n'affecte que légèrement la faisabilité de la gestion de la flexibilité.

Pour les batteries, en tenant compte de la baisse rapide des coûts, nous envisageons un scénario avec un développement significatif de la capacité de stockage par batterie dans la région, atteignant 500 MW d'ici 2050. Cette augmentation de la capacité de stockage impacte positivement le mix de flexibilité, même si elle semble insuffisante par rapport aux besoins de flexibilité réels.

Enfin, nous analysons un scénario excluant les centrales à combustibles fossiles, pour voir si le système peut fournir de la flexibilité sans ces technologies et soutenir l'inclusion des énergies renouvelables. Les résultats sont similaires à ceux du scénario de développement des batteries, suggérant que le système pourrait être géré sans recourir aux technologies fossiles, surtout si le développement de la technologie des batteries se poursuit comme prévu.

Ces analyses de sensibilité mettent en évidence l'importance des différentes technologies de flexibilité et la nécessité de planifier leur évolution pour assurer la stabilité et la fiabilité du système énergétique d'Occitanie dans le futur.

## 5. Conclusion

La conclusion met en lumière l'importance de comprendre et d'adresser les besoins en flexibilité dans les systèmes énergétiques décarbonés, en se concentrant sur la région Occitanie en France. Avec la transition mondiale vers un avenir énergétique durable et faible en carbone, les systèmes de puissance doivent s'adapter pour intégrer une proportion croissante de VRE. Ce chapitre, à travers plusieurs scénarios et l'utilisation d'un modèle d'optimisation basé sur l'ordre de mérite, souligne la nécessité d'investissements significatifs en capacités flexibles d'ici 2050. Nos résultats indiquent que l'hydraulique de haute chute, le nucléaire et les technologies basées sur le marché joueront un rôle crucial dans le soutien à l'intégration des capacités VRE, assurant un équilibre stable entre l'offre et la demande.



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Nous découvrons que pour les scénarios REPOS 2050 et *Electrification Intensive*, le mix actuel de flexibilité de la région Occitanie ne peut pas satisfaire les besoins en flexibilité projetés environ 20% du temps, en particulier en raison des exigences de flexibilité négative induites par les grandes parts de renouvelables intermittentes.

Nos analyses de sensibilité offrent des perspectives sur les résultats potentiels qui pourraient affecter la fourniture de flexibilité dans le futur système électrique d'Occitanie. Ces analyses soulignent l'importance de considérer divers facteurs et incertitudes dans la planification des investissements en infrastructures énergétiques. Par exemple, l'arrêt des réacteurs nucléaires pourrait entraîner une réduction des coûts de flexibilité pour les scénarios les plus ambitieux comme REPOS 2050. Nous avons également montré que l'équilibre entre l'offre et la demande d'électricité peut être atteint sans l'aide de technologies intensives en carbone.

Enfin, nous soulignons que le point de vue régional adopté dans cette étude dépend du réseau national ou supranational. Nos résultats démontrent que pour environ 20% du temps, des scénarios ambitieux tels que REPOS 2050 et *Electrification Intensive* dépendent entièrement des infrastructures à l'échelle du réseau pour atteindre l'équilibre offre-demande. Cela souligne l'importance du réseau national ainsi que des investissements dans les capacités du réseau pour l'intégration des VRE dans les systèmes énergétiques régionaux.

En résumé, cette étude apporte des perspectives et méthodologies précieuses pour comprendre et aborder les besoins de flexibilité des systèmes énergétiques décarbonés. En analysant le cas de la région Occitanie, nous avons démontré l'importance des investissements en capacités flexibles et la nécessité d'une approche proactive et adaptative pour planifier

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l'avenir des systèmes énergétiques. Il est crucial de continuer à surveiller et évaluer l'efficacité des stratégies mises en œuvre et de les adapter au besoin. Des études complémentaires devraient également explorer la flexibilité du côté de la demande, qui sera déterminante pour réussir la transition énergétique.



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# THE FUTURE OF POWER SYSTEM FLEXIBILITY IN OCCITANIE: A SCENARIO ANALYSIS

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## 1. Introduction

Transitioning to low-carbon energy systems is compulsory to achieve climate goals. In Europe, the Net-Zero target has been set for the year 2050 and is now backed by several regulatory mechanisms including the Fit for 55 package that follows the strengthening of the intermediate 2030 climate objective. This set of proposals already sets ambitious targets for the reduction of greenhouse gases emissions in the energy sector by 2030. For instance, the package includes a revision of the renewable energy directive, switching from a target of 32% to 42.5% of renewables in the European energy mix by 2030 [European Commission, 2022]. At the national level, the French government has also issued a Low Carbon National Strategy (SNBC) in 2015. Part of this strategy is the Pluriannual Energy Program (PPE) [French Ministry of ecological and sustainable transition, 2019] that comes to define precise targets for the energy sector in terms of renewable capacities, security of supply or energy efficiencies. In parallel, administrative French regions have also come up with local energy policies by their own. This is the case of region Occitanie, located in the south of the country, and thus benefiting from significant solar irradiation and regular wind levels. Aiming at

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becoming the first European region with a positive energy balance, the Occitanie region has issued an energy transition scenario, named *Région à Energie Positive* (REPOS) 2050, in which VRE capacities are increasingly introduced at the regional level [Occitanie region, 2017].

Energy transition scenarios have also been developed for several years with different points of view. Indeed, besides the policymakers, the civil society as well as public companies have also contributed to the debate about the energy schemes needed to achieve the transition. Among them, we find the négaWatt initiative that promotes a transition path relying on societal changes, such as a switch towards environmentally friendly mobility (walking, bike, carpooling), and intense efforts of energy efficiency [négaWatt Association, 2022]. With a less optimistic point of view, Réseau de Transport d'Electricité (RTE), the French transmission system operator (TSO), also proposed in its “Energy Futures” several scenarios of low-carbon transition for the electricity sector. Their projections have been updated in 2023 to account for a possible higher electricity consumption (between 500 and 640 TWh/year at the national level) than previously proposed [RTE, 2022]. Here again, intermittent renewable generation provides a large share of the total electricity generation, with nonetheless a greater role played by nuclear.

The rapid introduction of VRE capacities in the generation mix poses new questions. Indeed, historically, power systems have been structured in centralized way, with large controllable production capacities linked to consumption hubs via high voltage transmission lines. Solving the optimal dispatch of generation technologies is therefore logically performed at the national level, and now that power systems are interconnected between several

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countries, it is even managed at the supranational level. However, decentralized VRE capacities are now changing the energy landscape. They are indeed located closer to consumptions hubs and their intermittency, combined with a lack of significant storage capacities, offers new opportunities and challenges that a regional point of view could address. From managing local congestions issues to adapt the distribution grid soundly, including the creation of new electricity related products and the implementation of local energy policies, issues that emerge with the development of VRE appear to be analyzed with a new point of view, the regional one, that we propose to adopt in this paper. This regional approach is complementary to the grid-scale approach, and we must underline the fact that the regional power system, as we envisage it, can simply not exist without the already existing grid-scale power system. Still, our regional approach is motivated by the existence of regional energy policies, which themselves are products of an administrative and political splitting of the national territory into regions.

Our purpose in this study is to address the issue of power system flexibility with a decentralized point of view, using scenario analysis and a linear optimization model. Let's start with the regional aspect of this study : in the academic literature we have found only one paper [Iwai et al., 2014] that adopts a regional perspective when proposing an energy-related scenario analysis. If energy transition scenarios have been well explored by various authors, they always take a national or supranational point of view [Spiecker and Weber, 2014]. In their 2022 paper, Thimet and Mavromatidis propose a review of model-based transition path scenarios for France, Germany, Italy and Switzerland. They explore the various combinations of technologies that can lead these countries to reach their climate goals. Noticeably, scenarios that meet environmental targets are also the ones with high shares of wind and solar capacities [Thimat and Mavromatidis, 2022]. When some papers tend to focus on a specific

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set of technologies to study [Kaplan and Witt, 2019 ; Decker et al., 2019], others detail precise methodologies to consider when building energy transition scenarios [Li et al., 2020 ; Li et al., 2022]. Other approaches propose to analyze the transition path of independent island power systems, but this point of view is different from ours as our proposal of a regional power system is fully integrated within the national power system, which is not the case for independent island power systems [Zafeiratou et Spataru, 2018 ; Harewood et al., 2022].

In addition, these previous energy-transition studies did not consider the issue of power system flexibility, which is critically linked to the development of VRE. Indeed, without adopting a regional perspective, it is difficult to account for the local production conditions and consumption patterns that enable an efficient matching of supply and demand. Said otherworldly, in the absence of large-scale storage capabilities, a regional approach is well suited to not only address the grid congestion that emerge with VRE inclusion, but also to take profit of the proximity between supply and demand in order to reduce operational costs.

Recently, the topic of power system flexibility has indeed emerged as a critical issue to consider when incorporating large shares of renewables in the future power systems. Simply put, power system flexibility refers to the ability of a given power system to cope with rapid changes either in load or generation. More precisely, and as defined more extensively in the introductory part of this thesis, “*power system flexibility is the inherent and dynamic capability of an electrical grid to promptly, seamlessly, and efficiently adapt to the continuous fluctuations in both electricity generation and consumption*”. As controllable generation is mostly driven by fossil-fueled technologies (CCGT, Oil and Gas fired turbines), it will

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become scarce in future electricity mix that ambition to be CO<sub>2</sub> neutral. Therefore, it becomes compulsory to accompany energy transition scenarios with an in-depth reflection about the management of power system flexibility. This is precisely the topic we want to address in this paper. With the help of a specifically designed flexibility management model, we aim to analyze how the future flexibility requirements induced by transition scenarios can be served. Our contribution to the literature is therefore twofold: we propose new transition scenarios for a regional power system, namely Occitanie power system, and analyze them under the specific scope of power system flexibility. More precisely, we present three scenarios for the 2050 Residual Load (RL) of Occitanie power system and solve our merit-order based flexibility management model for a full year, at a half-hourly timescale. Note that the inner workings of the flexibility management model have been described in a previous chapter. Our methodology is therefore divided into three sections: first, we build scenarios of RL for the year 2050, using technological, political and economic assumptions for the Occitanie region. Second, we use our optimization model to solve the optimal dispatch of flexible units, with baseline costs and capacities parameters. Finally, we present alternative scenarios, or sensitivity analyses, in which we move the baseline parameters of the model to represent various situations that could occur on the Occitanie power system in 2050.

The regional approach adopted in this work, focusing on the Occitanie power system, offers several unique advantages. It allows for a more granular analysis of the power system, accounting for local resource availability, consumption patterns, and infrastructure constraints. This level of detail could uncover local solutions that may be overlooked in broader analyses, ensuring our model accurately reflects the unique challenges and opportunities Occitanie presents. Our study also serves to inform local policymaking, as the growing role of regional and local authorities in energy planning necessitates locally relevant



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data and research. Additionally, the methods and findings from our research can act as a model for other regions undergoing similar energy transitions, offering transferable lessons and strategies, thereby contributing to the broader body of knowledge on regional energy transitions. Moreover, as VRE lift a technological barrier towards decentralized production, it appears economical for consumers to become prosumers, i.e., that they invest to consume the energy they produce. The virtuous learning-adoption circle that enabled steep costs reductions was favored by feed-in tariffs strategies that have largely contributed to the development of local VRE capacities. This also comes to justify the regional approach we take, as by focusing on this level, we can facilitate more effective engagement with local stakeholders. Finally, by taking this point of view, we hope to uncover the intricate interactions that shape the relation between the regional and grid-scale power systems.

The rest of the paper is organized as follows. Section 2 will review the methodology we adopted to build the three scenarios of Occitanie power system RL. Then, in Section 3, the flexibility management model will be solved using these three scenarios as demands for flexibility, and baseline parameters for the supply side. The aim of this section is to identify which aspects of the current Occitanie flexibility mix could be improved to serve the estimated requirements. Section 4 will be dedicated to study the sensitivity of the modeling results to various parameters of the *Optimiflex* model, including nuclear capacity, batteries costs and capacities and hydropower availability, as well as fossil fueled plants availability. Finally, Section 5 will propose a conclusion for this work and will present future potential research avenues.

## 2. Methodology

### A. The RL as an approximator for flexibility requirements

As our purpose in this paper is to analyze the flexibility management of the future Occitanie power system, we need first to approximate the flexibility requirements that need to be served. This is done, as in our previous chapters, by using the RL function of the given power system. The RL represents the amount of electricity that needs to be produced to satisfy the demand once all the electricity produced by variable sources has been injected into the grid. In other terms, the RL equals the total electricity demand at time  $t$  ( $D_t$ ) reduced by the production of variable sources ( $P_t^{PV} + P_t^{TW} + P_t^{OW}$  respectively the production of solar PV, terrestrial wind, and offshore wind). We end up with Equation (1) that naturally embodies the RL concept in mathematical terms.

$$(1) RL_t^D = D_t - (P_t^{PV} + P_t^{TW} + P_t^{OW})$$

The RL function is a good approximator for the demand for flexibility, as it encompasses the inelastic electricity consumption and the uncontrollable generation of VRE sources. Therefore, the RL provides us with the amount of electricity that needs to be generated by controllable means *e.g.*, conventional generation, storage, market exchanges...

In chapters 1 and 2, we already have discussed the fundamental aspects of Occitanie RL. It is however important to mention that the Occitanie RL is subject to strong seasonal patterns that increase the demand for positive flexibility during winter and negative flexibility

demand during summer. It is to be noted that positive flexibility demand is equivalent to a demand for additional power to satisfy the consumption, while negative flexibility refers to a demand for a storage or at least evacuation of the regional production surplus towards the national grid. The high variability (1068 MW of standard deviation for the 2019 Occitanie RL) of the RL is also one its core characteristics. This underlines the fact that flexible capacities must be able to ramp up or down fast to satisfy the flexibility requirements.

## B. Building the *Business-as-usual* Occitanie RL scenario

In a first part, we aim to explore what would be the flexibility requirements of the Occitanie power system if the trajectory of electricity consumption and renewable development would remain the same as the past decade until the year 2050. To achieve this task, we will make use of historical data of both electricity consumption and VRE capacities for the region Occitanie.

The electricity consumption data we use is coming from the open-data platform of region Occitanie<sup>9</sup>, and covers the amount of annual electricity consumption for each sector of the economy, for a period spanning from 1990 to 2020. With the aim of having more representative data, we exclude the year 2020 and we will use only the 2006-2019 period. During this period the electricity consumption of the residential sector as well as the consumption from the tertiary sector both increased slightly, respectively by yearly averages of 1.10% and 0.52%. Meanwhile, the consumption from the industrial, agricultural and transport sectors respectively decreased by 0.60%, 0.005% and 0.10% on a yearly average

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<sup>9</sup> Available at [https://data.laregion.fr/explore/dataset/historique-de-la-consommation-denergie-en-occitanie/table/?sort=secteur&refine.vecteur\\_energetique=Electricit%C3%A9](https://data.laregion.fr/explore/dataset/historique-de-la-consommation-denergie-en-occitanie/table/?sort=secteur&refine.vecteur_energetique=Electricit%C3%A9)

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basis. These trends indicate a relatively stable pattern of electricity consumption in Occitanie over the past decade or so.

However, to deepen our understanding of future electricity consumption, we must consider the potential impact of economic growth. Economic growth often correlates with increased energy use, but the relationship can be complex, influenced by factors such as the energy efficiency of different sectors, the proportion of growth in energy-intensive industries, and policy measures designed to curb energy use.

To incorporate the effects of economic growth into our scenario, we first obtain the regional economic growth projections for the Occitanie region up to the year 2050. From the French national statistics office<sup>10</sup>, we know that over the 2006-2019 period, the average rate of growth for the Occitanie economy was 1.2%, with a significant increasing trend after 2014. Specifically, before the COVID crisis, the Occitanie GDP grew by 2.0% between 2016 and 2017, then by 2.4% between 2017 and 2018, before falling back to 1.7% between 2018 and 2019. After the COVID crisis, GDP increased between 2021 and 2022 by 2.5% due to economic recovery. It will probably be lower in 2023 due to the Ukrainian crisis and inflation. More generally, the actual average growth rate for the Occitanie region between 1990 and 2019 is exactly 2%, which is also the hypothesis retained (1,9% to be exact) in the Occitanie regional land development scheme for 2040<sup>11</sup>. For these reasons, we propose that the regional economy is projected to grow at an average rate of 2% per annum over the next three decades.

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<sup>10</sup> Available at <https://www.insee.fr/fr/statistiques/5020211>

<sup>11</sup> Available at <https://www.prefectures-regions.gouv.fr/occitanie/Documents-publications/Le-SRADDET-de-la-region-Occitanie>

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This results in an economy growing up to 284 101 million euros per year in 2050, starting from a 156 844 million in 2019.

Now to estimate the increase in electricity consumption that results from these hypotheses, we need to study the relationship between energy and the economy, electricity being a part of the general energy mix of a given territory. However, the relationship between economic growth and energy consumption is not a direct one. Indeed, this relationship is deemed to be non-linear and still nowadays the four hypotheses (unidirectional towards growth, unidirectional towards energy consumption, bidirectional, neutral) are equally spread amongst the literature. This is due to the concept of energy intensity - the amount of energy required to produce one unit of economic output. As economies grow and evolve, we could naturally think that they become less energy-intensive due to advancements in technology, shifts in the economic structure towards less energy-intensive sectors, and policy measures aimed at promoting energy efficiency. However, it is unclear how the rebound effect plays its role regarding the overall energy consumption. At the end of the day, projecting the energy intensity of a region remains a highly hypothetical exercise.

To account for these factors, we analyze the energy intensity of the Occitanie region's economy. Besides the industrial basin around Toulouse, it is well known that the Occitanie economy is mostly dominated by services and agriculture. As we do not foresee a development of the industry in the region for the decades to come, we can expect that the energy intensity of the Occitanie economy will remain at least stable but most probably will decrease. As we do not have exact data for the Occitanie region, let's suppose that over the past decade, the energy intensity of the region's economy has been decreasing by an average

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of 1% per year, mostly due to industrial and transport increased efficiencies as well as renovations in the building sector, in the same way the national trend<sup>12</sup> did. Assuming this rate of decrease in energy intensity continues, we can expect the energy intensity of the Occitanie economy in 2050 to be around 70% of its current level, according to the cumulated average growth rate calculated over the period (to be exact, we end up with an energy intensity rate of around 66%, we retain 70% for the ease of calculation). This means that for each unit of economic output, the region would be using 30% less energy than it does today. However, as the economy grows, even at this reduced energy intensity, the absolute amount of energy consumed could still increase, and especially if we account for a significant rebound effect that does at least equals the gains in energy efficiency. If we apply this 70% energy intensity figure to the projected economic output in 2050, we can estimate the total energy demand for the region. We therefore multiply 70% by the estimated economic output for 2050 (284 101 million euros) and find a total energy demand of 198 TWh per year. This figure can seem high compared to the 125 TWh consumed in 2019 by the region, but it is based on a continuous growth of the economy (2% per annum) and encompasses all energy uses. In 2019, around 34 TWh of electricity only were consumed in Occitanie, which represents an increase by 54% compared to the 1990 level. Meanwhile, the Occitanie economy grew at an average rate of 2.3% over the same period. We realize here that our projections for the increase in energy consumption are grounded on actual trends of the Occitanie region.

For the electricity sector specifically, we need to consider additional factors. As the economy grows, there could be a higher demand for electrically powered technologies, especially in the residential, commercial, and transport sectors. The process of electrification,

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<sup>12</sup> Available at <https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-energie-2021/8-efficacite-energetique>

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driven by the transition to low-carbon technologies, could increase the share of electricity in the region's total energy use. For instance, in RTE's Energy Futures 2050, electricity consumption is expected to increase by +35% between now and 2050, mainly due to the electrification of transport, hydrogen production and reindustrialization. This would result in electricity accounting for 55% of final energy consumption in France in 2050<sup>13</sup>. That said, our *Business-as-Usual* scenario is based on projections of historical values and does not seek to consider all new uses of electricity (this will be done in the *Intensive Electrification* scenario). Furthermore, we do not wish to make any assumptions about the reindustrialization of the Occitanie region between now and 2050 (this is considered to be outside the scope of this work). We have therefore chosen to make the share of electricity remaining fixed in the total energy demand. The current value for the share of electricity within the total energy demand is around 20%<sup>14</sup>, according to the source provided. Applying this share to our projected total energy demand gives us the projected electricity demand. Said otherworldly, we multiply this 20% electricity share by the overall energy demand of 198 TWh per year. When we perform this calculation, we end up with a total yearly consumption for the region Occitanie of 39.41 TWh, or an increase of 22% compared to the 2019 level.

After this detailed calculation, we obtain the overall increase of the electricity consumption for the region by 2050: 22%. We then simply apply this percentage of increase to historical half-hourly consumption time-series<sup>15</sup> in order to have a representation of what would be the trajectory of a full year of consumption for the region in 2050. To complete our scenario of flexibility requirements, we now have to include a projection of the VRE

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<sup>13</sup> Available at <https://www.lesechos.fr/industrie-services/energie-environnement/pourquoi-la-demande-delectricite-devrait-exploser-dici-a-2050-1358134#:~:text=De%201.600%20TWh%20en%202020,de%20l'%C3%A9nergie%20finale%20consomm%C3%A9e>.

<sup>14</sup> Available at <https://jancovici.com/transition-energetique/electricite/quelle-part-de-lelectricite-dans-la-consommation-francaise-denergie/>

<sup>15</sup> Available at [https://odre.opendatasoft.com/explore/dataset/eco2mix-regional-cons-def/export/?disjunctive.libelle\\_region&disjunctive.nature&refine.libelle\\_region=Occitanie&refine.date\\_heure=2018](https://odre.opendatasoft.com/explore/dataset/eco2mix-regional-cons-def/export/?disjunctive.libelle_region&disjunctive.nature&refine.libelle_region=Occitanie&refine.date_heure=2018)

generation that follows the observed tendencies of the past years. To perform this, we take the average voluminal increase of VRE capacities observed between 2006 and 2019. The data we use is collected here from the *Open Data Réseaux Energies* platform<sup>16</sup>, in which are gathered various datasets coming from French energy stakeholders. During the 2006-2019 period, solar PV and wind capacities increased in average by respectively 155 MW and 103 MW per year<sup>17</sup>. If we continue this trend up to the year 2050, the expected installed capacities will be around 4 750 MW for wind and 6 810 MW for solar PV. By multiplying these capacities by the observed load factors for the year 2019, we can calculate the expected half-hourly production of VRE technologies for the *Business-as-Usual 2050* scenario. As a final step, we need to use Equation (1) to obtain the expected Residual Load of Occitanie for the *Business-as-Usual 2050* scenario. We present a graphical view of this RL in Figure 16.

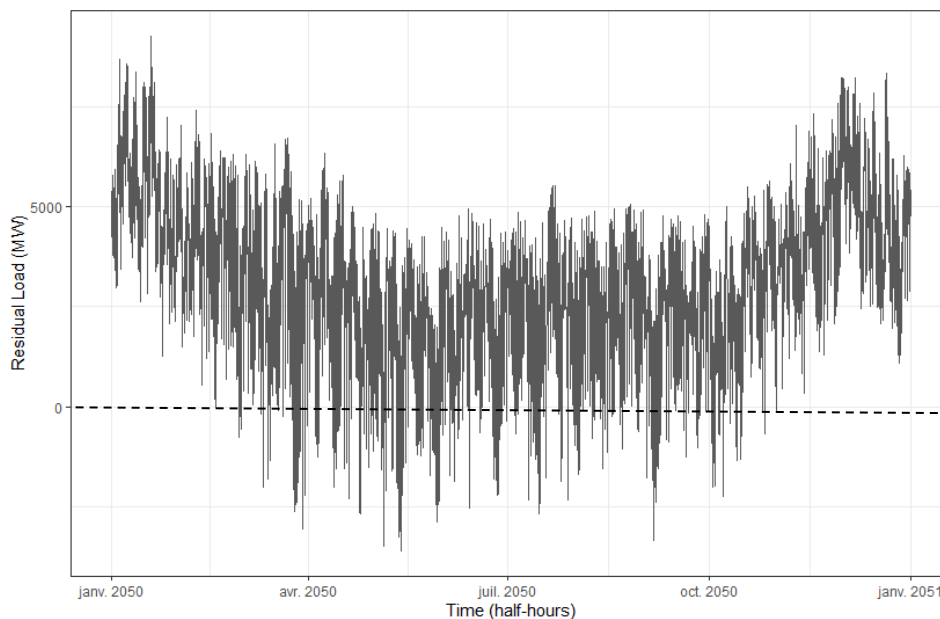


Figure 16 : . Half-hourly residual load of Occitanie power system in the 2050 *Business-as-Usual* scenario

With a standard deviation of around 2007 MW, the 2050 *Business-as-Usual* RL is twice as variable as the reference RL of 2019. This is due to the increases in VRE generation,

<sup>16</sup> Available at <https://odre.opendatasoft.com/explore/dataset/parc-regional-annuel-prod-eolien-solaire/export/?disjunctive.region&refine.region=Occitanie&sort=annee>

<sup>17</sup> Note that the figures are affected by the feed-in tariffs policy that enabled a fast development of the VRE capacities over the 2000-2010 decades.



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which particularly affects the variability of the series during summer months. Indeed, starting from April, the RL becomes both positive and negative a fair amount of time due to the reduction of the consumption and the increase in solar production. This reveals us that even at the current pace of VRE deployment, significant amounts of negative flexibility will be required to absorb the excess energy produced within the region. Said in another way, if we apply current trends (static 2% economy growth rate, 1% decrease in energy intensity, same electricity share in energy demand, static increase of VRE capacities), we will end up in a situation in which the amount of locally produced electricity can exceed the demand of the Occitanie region, particularly during summer months. This already reveals us that the role of the national grid to absorb these surpluses will be crucial, as well as the role of local storage technologies. However, these results have to be mitigated with a potential increase in consumption in summer due to tourism and electric cooling systems, two features that are and will remain inherent to the Occitanie summer economy.

After proposing a *Business-as-Usual* scenario in which current tendencies in terms of electricity consumption and VRE deployment are continued until the year 2050, we will now introduce two variants that represent alternative trajectories for the Occitanie power system.

## C. The REPOS 2050 scenario

The first of these alternative trajectories is named after the scenario that has been proposed by the Occitanie region in 2017. The REPOS 2050 scenario is indeed a proposal to make Occitanie the first French region with a positive energy balance by 2050. In this very ambitious plan, the region is supposed to decrease its final energy consumption by 39% by the year 2050, which represents a significant effort compared to the 58% increase of final energy demand envisioned in the *Business-as-Usual* scenario. In other words, in this scenario, the region should cut around 49 TWh of energy demand until 2050, or around 1.6 TWh of energy demand every year. We cannot emphasize enough that this scenario sets very ambitious, almost bold claims.

As we will present it in more details, it will become clear that the REPOS 2050 scenario relies on intensive energy efficiency efforts as well as a decrease in energy consumption, driven by new behaviors. These efforts are incentivized through policy measures such as tax credit for building renovation, free access to public transportation, or subsidies for companies investing in low-energy consumption sectors. It goes without saying that increases in energy prices could also end up with a decrease in energy consumption, as we could observe during the 2022-2023 winter in France.

Using the projections realized by the Occitanie region, it is expected, in this scenario, that the total regional electricity consumption will decrease by around 7% compared to its 2015 level. Compared to the 9%<sup>18</sup> decreased observed in France during winter 2023, this target seems achievable. However, as we have seen in the previous section, the electricity consumption of Occitanie slightly increased in average between 2015 and 2019, meaning that the region is already not on track to follow the REPOS 2050 guidelines. In this variant, it is

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<sup>18</sup> Available at <https://assets.rte-france.com/prod/public/2023-02/2023-02-24-reactualisation-hiver.pdf>

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expected that efficiencies are realized in the residential and tertiary sectors due to a vast program of buildings renovations. These renovations, as mentioned before, should be incentivized via public spendings, which poses the question of the financing of such measures. In parallel, a decrease in the industrial activity will lead the region to decrease its industrial electricity consumption. It is to be noted that the potential of industrial decrease remains low for the Occitanie region, which has already a services and agriculture based economy. The region will thus not be in capacity to reduce a lot its industrial consumption, like what happened in France in winter 2023 to achieve the 10% decrease. It will therefore heavily rely on residential and tertiary decreases, which, again, will rely on public spendings. These two factors combined (industrial and residential/tertiary decreases) should end up in the previously mentioned decrease of the total electricity consumption, even if the consumption of the transport sectors is expected to increase drastically.

Indeed, as the region is in this scenario committed to transform its energy system into a more sustainable one, voluntary policies are implemented to shift the traditional fossil-fueled vehicles fleet towards an electricity fueled one. This results in an increase of more than 4.3 TWh per year for the Occitanie transport sector. This figure underlines the very fast changes needed to achieve the energy transition and should be tempered with the bold hypothesis that the majority of the vehicle fleet will be electric by 2050 in Occitanie. That being said, we understand clearly that the decrease of the total electricity consumption heavily relies on the rate at which buildings are renovated and adopt efficient strategies to reduce their electricity consumption, which, so far, remains highly uncertain. Still, our aim in this paper is to propose various trajectories for the Occitanie power system, we will thus use this 7% decrease of the electricity consumption on historical time-series to produce a sample of what could be the half-hourly electricity consumption of the region for the year 2050.

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Transforming the region into a positive energy-balance one requires intense efforts on the demand side, but also implies that the production side is heavily modified too. In the REPOS 2050 scenario, the development of variable and renewable electricity generation capacities is accelerated. By inciting both large and small private stakeholders as well as public institutions to invest in solar PV capacities, the region expects a total capacity of 15 070 MW for PV by 2050, which represents a huge increase compared to the 1 814 MW installed in 2019 in Occitanie. Wind technologies are also prioritized, as the region benefits from significant amounts of regular wind all the year. Therefore, the region should have a total of 5 500 MW of onshore wind capacities by the year 2050, which here again is a significant increase compared to the 1 526 installed in 2019 in Occitanie. It is also worth mentioning that the region expects to unlock its offshore wind potential by implementing 3 000 MW of offshore wind turbines by 2050. The methodology used to produce the REPOS 2050 RL is similar to the one used for the *Business-as-Usual* scenario: we use historical load factors of VRE technologies and multiply them by the expected capacities of the year 2050. For the offshore wind technology, we do not have access to historical production data, therefore we use a dedicated application<sup>19</sup> (created by Stefan Pfenninger (TU Delft) and Iain Staffell (Imperial College London)) that calculates load factors time-series given a location and a wind turbine technology, using the most recent satellite data available and the GSEE model [Pfenninger and Staffell, 2016]. Once we have obtained our generation time series for all the VRE technologies, we simply subtract the sum of the VRE production time series to the consumption to get our RL time-series. A graphical representation of the REPOS 2050 RL is provided in Figure 17.

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<sup>19</sup> <https://www.renewables.ninja/>

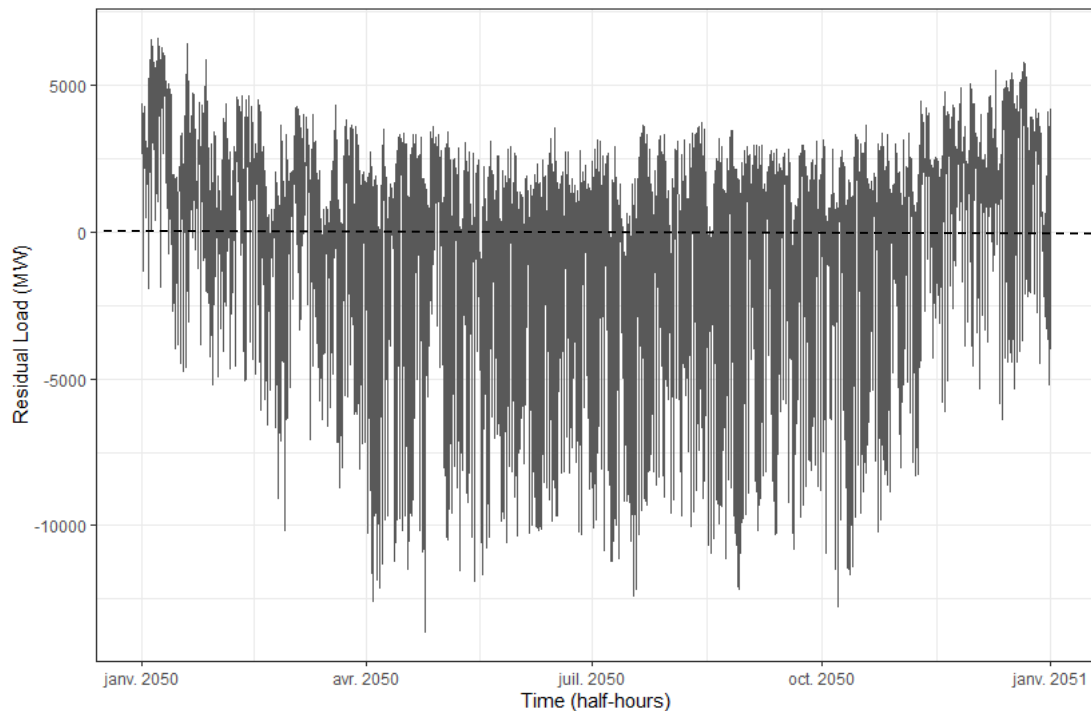


Figure 17 : Half-hourly Residual Load of the Occitanie power system in the REPOS 2050 scenario

As we can see on Figure 17, the Residual Load in this scenario becomes negative for most of the time, meaning that the Occitanie power system has indeed reached the level of positive power balance. This fact also underlines the necessity for the system to have significant amounts of negative flexibility capacities, but also the fact that in this scenario the regional power system would rely even more on the national grid, which can translate into a need for investments in grid capacities. In this scenario, the usual winter-summer seasonal pattern of the consumption moves to an increase of the solar PV production between the months of March and October, which is back during winter by a increase in wind generation. The variability also intensifies in this scenario, as the standard deviation of the series reaches a level of 3 339 MW, revealing a need for flexibility capacities that can ramp up or down in a fast and efficient way. For a graphical comparison with the *Business-as-Usual* and *Intensive Electrification* scenarios, please refer to Figure 29 in appendix 2.A. A reminder of the main hypothesis proposed to build the three scenarios is also available in Table 14 in appendix 2.A.

## D. Exploring a massive electrification pathway: the *Intensive Electrification* scenario

In the two previous sections, we have respectively presented a middle and a low trajectory for the electricity consumption of the Occitanie region. To complete our landscape of potential pathways for the region's flexibility requirements, we now propose an Intensive Electrification scenario in which new modes of living as well as new opportunities for the industrial use of electricity take place. Due to these changes, the overall electricity consumption drastically increases, and this increase is not compensated by energy efficiency efforts. Our aim is here to represent a situation in which the shift from fossil fuels to electricity results in a society heavily relying on this last energy carrier. In addition, the situation depicted in this scenario does not make any assumption on behavioral changes, mostly because the uncertainties regarding the financing of public spendings needed to achieve such changes are high. To meet the increasing needs in terms of electricity demand, the production capacities also require to be expanded to ensure a security of supply for the region.

What makes this scenario original but also complex to calibrate is that it is hard to predict the potential increase of electricity consumption that would result from a massive electrification movement. For the sake of simplicity, we propose in this paper to reduce the number of potential variables to move to affect the electricity consumption to three, namely: the electric heating and air-cooling equipment rate of residential and tertiary buildings, the size of the electric vehicles fleet, and the amount of electrolysis-produced hydrogen.

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In France, the share of residential and tertiary buildings that are heated or cooled via an electric device (including heat-pumps) oscillate around 30% since the 2010s<sup>20</sup>. It might be slightly higher in Occitanie due to the recent immigration movement that ended up in the creation of numerous new residential buildings equipped with low-efficiency electric heating, but for the sake of simplicity we will keep this 30% number for our estimates. To reach climate goals, one can imagine that by 2050 most of the gas-fired and fuel oil-fired heaters shares (respectively 39% and 14%) are replaced by electric devices, notably by promoting heat-pumps. Therefore, we propose that the equipment rate in electric heating or cooling systems reaches 70% in the Occitanie region by 2050, leaving only 13% of gas fired heating in the residential and tertiary sectors the remaining 17% being covered by wood and fuel systems. We know that a heat-pump approximatively consumes 5 100 KWh per year for a 100m<sup>2</sup> typical house<sup>21</sup>. This figure obviously is a large approximate that depends on the type of equipment and the building's volume. Besides this, the number of residential buildings in Occitanie has been increasing by 1.3% per year since 2012<sup>22</sup> and could thus reach a total of 3 850 000 by 2050. Unfortunately, we do not have any information on the number of tertiary buildings. However, we also know that the share of electricity consumption associated with heating or cooling represents 66% of the overall consumption of a residential building<sup>23</sup>. Without going to deep in technical details, it remains difficult to estimate how this increase in electric heating or cooling systems will affect the residential and tertiary electricity consumptions. In parallel, measures of energy efficiency, that are far less ambitious than in the REPOS scenario, could also have an effect on the overall residential and tertiary

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<sup>20</sup> Available at <https://www.lenergiesoutcompris.fr/actualites-conseils/evolution-des-parts-de-marche-des-energies-de-chauffage-47364>

<sup>21</sup> Available at <https://www.effy.fr/travaux-energetique/chauffage/pompe-a-chaleur/consommation-electrique>

<sup>22</sup> Available at [https://www.occitanie.developpement-durable.gouv.fr/IMG/pdf/ccl2021\\_valide-et-corrige\\_internet.pdf](https://www.occitanie.developpement-durable.gouv.fr/IMG/pdf/ccl2021_valide-et-corrige_internet.pdf)

<sup>23</sup> Available at <https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-du-logement-2022/29-consommation-energie#:~:text=Repr%C3%A9sentant%2057%20%25%20du%20parc%20des,eau%20chaude%20et%20la%20cuisson>

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electricity consumption. Therefore, we propose an estimate of the shift towards electric heating and cooling resulting in an increase of 25% of electricity consumption in the residential and the tertiary sectors.

Similarly, hydrogen production depends on many factors such as investment in electrolysis capacity, support policies for the sector, and the deployment of the hydrogen transport network. Most projects for electrolyzers powered by intermittent energy are still at the demonstration stage. Indeed, the costs of producing hydrogen via electrolysis remain high and do not foresee the widespread deployment of the technology until around 2035-2040. It is therefore proposed that the newly installed Power-to-Gas (PtG) electrolysis capacities in Occitanie by 2050 do not exceed 500 MW, equivalent to an increase in industrial electricity consumption of around 3,000 GWh/year (using a 70% load factor<sup>24</sup>, which heavily depends on meteorological conditions and technology). It should be noted that these capacities represent a means of storing intermittent electricity. However, the debate around hydrogen production has mostly been oriented towards the use of green hydrogen to cut of emissions from sectors such as chemical industry or heavy-duty transport. In our case, this possibility of storage is directly embodied by the increase in electricity consumption and therefore in residual demand. We will therefore not optimize the use of PtG, as we consider its production necessary for the hydrogen sector (especially for the transport and chemical industries) and therefore not linked to an apparent price signal on the flexibility market.

Regarding the electricity consumption of transportation, this scenario is voluntary in the sense that the majority of the light vehicle fleet (similar to the 2050 REPOS scenario)

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<sup>24</sup> Available at [https://hypster-project.eu/wp-content/uploads/2021/10/Deliverable\\_1-1\\_H2-production\\_and\\_consumption\\_profiles.pdf](https://hypster-project.eu/wp-content/uploads/2021/10/Deliverable_1-1_H2-production_and_consumption_profiles.pdf)



becomes electric by 2050. In the *Intensive Electrification* scenario, we propose that the heavy vehicle fleet (public transportation and goods transportation) is mainly powered by hydrogen by 2050<sup>25</sup>.

Citing RTE *Energy Futures* scenarios, this article<sup>26</sup> mentions that the average consumption of an electric vehicle is around 1 800 kWh per year. We also know that the Occitanie current vehicle fleet is composed of around 3 627 000 vehicles<sup>27</sup>. Multiplying the number of vehicles by the average consumption gives us an increase of 6,528 TWh per year. It should be noted that this figure is a large estimate that could be affected by progress in battery technology. Indeed, the potential reversibility of electric vehicles batteries could be a game changer as it would represent a means of storing electricity, which would greatly help the introduction of both electric vehicles and VREs. However, this technology is still at a very early stage of development, but as we need to introduce a certain form of increased efficiency over time, we choose to pick a 5 TWh per year increase in electricity consumption due to the shift towards electric vehicles.

Finally, when all these increases are combined, total electricity consumption increases in this scenario by 39% compared to the 2019 level. Here, we are proposing a scenario in which the massive electrification of uses (industry, transportation, heating) is not compensated by energy efficiencies, which implies a significant increase in total electricity consumption within the region. To meet this significant need, we propose a large increase in intermittent renewable capacities in this scenario, up to the exploitation of almost 50% of the region's full potential in photovoltaic and wind energy by 2050. As a result, onshore wind,

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<sup>25</sup> Available at <https://www.laregion.fr/L-Hydrogene-vert-se-construit-un-avenir-en-Occitanie>

<sup>26</sup> Available at <https://selectra.info/energie/actualites/insolite/consommation-vehicules-electriques-france-2040>

<sup>27</sup> Available at [https://actu.fr/societe/occitanie-le-parc-automobile-encore-tres-largement-domine-par-le-gazole-le-detail-par-departement\\_49190804.html](https://actu.fr/societe/occitanie-le-parc-automobile-encore-tres-largement-domine-par-le-gazole-le-detail-par-departement_49190804.html)

offshore wind, and solar PV capacities increase to 10 GW, 5 GW, and 20 GW respectively. To obtain the production curves for each technology, we will multiply the semi-hourly historical load factors to the new capacities as done for previous scenarios. We will make sure to generate new sets of load factors based on 2018 data. To generate variety compared to the REPOS scenario, we will also take 2018 consumption as a base for our calculation of the 2050 *Intensive Electrification* Residual Load. The idea is that if we keep the same year for both REPOS and *Intensive Electrification* scenarios, as the increase are only scalar increases, there wouldn't be so much diversity in the settling of the optimal dispatch for these two scenarios. Therefore, we believe that using 2018 data for the *Intensive Electrification* scenario will come to enrich our results without negatively impacting the reproducibility of the results and the overall demarch of comparing potential outcomes for the flexibility requirements of the Occitanie region.

Therefore, the RL for the intense electrification scenario takes the following form:

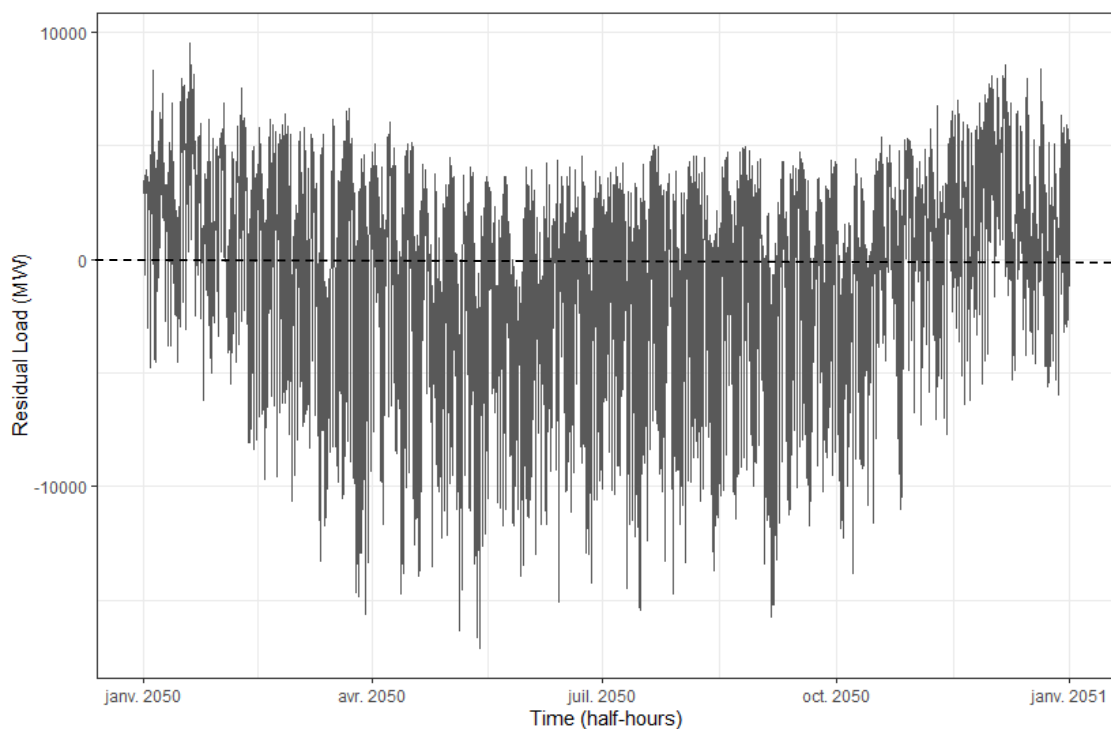


Figure 18 : Half-hourly Residual Load of the Occitanie power system in the Intensive Electrification scenario

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As expected, the RL is also much more variable here than on the original series and reaches more intense extremes than in the previous scenarios. It becomes even difficult to distinguish the seasonal pattern specific to electricity consumption as intermittent production generates significant variations. The cycles of the sun are exacerbated here, and the variability of offshore wind production also increases the degree of variability of the residual demand. While this scenario shows a great need for negative flexibility, the consumption peaks are intense enough to require large means of positive flexibility as well. Indeed, even if the consumption is largely augmented, the fact that 50% of the potential for VREs is exploited by 2050 introduces a production that is significantly higher than consumption for almost half of the periods considered. The solar production is especially affecting the shape of the RL, as a total capacity of 20 GW introduces a lot of variability due to the day-night production cycle. This results in a region producing vast amounts of energy that must either be stored or evacuated towards the national grid. Once again, we underline here the necessity of the regional power system to be included in a national grid that can absorb the local energy surplus.

As a conclusion for this section, we want to provide the reader with a table of descriptive statistics that will help apprehend the characteristics of the Residual Loads presented in these scenarios. Remember that summaries of the three scenarios (RL curves and main hypothesis) are available in appendix 2.A.

Series	Mean	St. Dev.	Med.	Min	Max	1 <sup>st</sup> Qu.	3 <sup>rd</sup> Qu.
Residual Load 2019	3 589	1 125	3 388	857	7 815	2 768	4 280
<i>Business-as-Usual</i> 2050 RL	3 016	2 007	3 176	-3 595	9 259	1 772	4 336
REPOS 2050 RL <i>Intensive</i>	-479	3 839	836	-13 614	6 603	-2 523	2 156
<i>Electrification</i> 2050 RL	-544	4 689	608	-17 107	9 522	-3 008	2 871

Table 8 : Descriptive statistics of half-hourly Occitanie Residual Load series, in MW

### 3. Baseline results

In the previous section, we described three potential outcomes for the 2050 Occitanie RL. The *Business-as-Usual* scenario continues the recent tendencies in terms of electricity consumption and renewables development, while the REPOS 2050 and the *Intensive electrification* scenarios describe two situations in which the increase in electricity consumption due to societal, technical, and economical changes is respectively compensated and not compensated by effort in energy efficiencies. Once we have calibrated these flexibility demands, we now want to assess how the flexibility mix could respond to it by making use of the *Optimiflex* model presented in a previous chapter.

#### A. Model parametrization

In a first part, we want to assess how the current flexibility mix of Occitanie region would react to the residual loads presented in the previous section. Therefore, we will use the current values for costs and capacities of the various flexibility means that are already installed in Occitanie. We call this choice of parameters the baseline parametrization. In this version of the *Optimiflex* model, flexibility technologies that are available to produce electricity on demand are hydraulic dams, nuclear

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reactors, biofuel plants, gas-fired power plants and oil-fired power plants. The technologies that are able to store electricity are Pumped Hydro Storage plants (PHS), and stationary batteries. It is worth recalling that as PHS systems use electricity to move water upwards, they increase the overall consumption of a given power system and thus reduce their need for negative flexibility by the same amount. Once water has been stored in the upper reservoir it can be then turbined to produce electricity again. Thus this technology can be considered as an effective storage technology. Finally, this version of the model introduces the Market Exchange technology or (Grid Exchange technology) as a means to both sell excess and buying lacking electricity. Therefore, the Market Exchange technology can be considered as a two-sided flexibility means, with a capacity limited by the size of the interconnections of the Occitanie transportation grid with its neighboring regions, and a price determined on the national market. For the sake of simplicity, we will take here an average yearly price as the marginal cost of this technology. As introduced in a previous paper, the two storage technologies suffer a constraint on their storage state, and the nuclear reactors cannot reduce their production lower than 20% of their overall capacity. Table 9 summarizes the parameters we will use to get baseline flexibility optimization results for the three considered scenarios.

Flexibility technology	Positive flexibility capacity (MW)	Negative flexibility (MW)	Marginal cost (€/MWh)
Biofuel plants	162	0	75
Hydraulic dams	2 337	0	25
PHS	1 500	-1 050	77
Nuclear reactors	2 620	0	28
Stationary batteries	2	-2	350
Oil-fired plants	152	0	115
Gas-fired plants	157	0	65
Market Exchange	4 500	-4 500	60

Table 9 : Capacities and cost parameters for the Baseline calibration of the *Optimiflex* model

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Considering these parameters, a merit-order chart of the technologies ranked according to their marginal cost and capacities can be drawn (see Figure 19). In this figure, we have considered a flexibility demand of 3 500 MW which is a typical value for an afternoon of January, when demand for electricity is high and solar PV production not at his maximum, to show which technology would be marginal in this situation. On the chart, we can see that the nuclear reactors is the marginal technology in this case. Notice that the Market Exchange technology is the one with the most available capacity, although not being the most cost-efficient in times of positive flexibility requirements. In this baseline configuration, expensive technologies that have a small capacity such as stationary batteries are expected to be called a very small amount of time if not at all. Solving the merit order for a demand of 3 500 MW ends up in a price equilibrium given by the marginal technology i.e., nuclear reactors. This price is the price of flexibility for this given level of demand and is thus equal to the marginal cost of nuclear reactors which is 28 €/MWh.

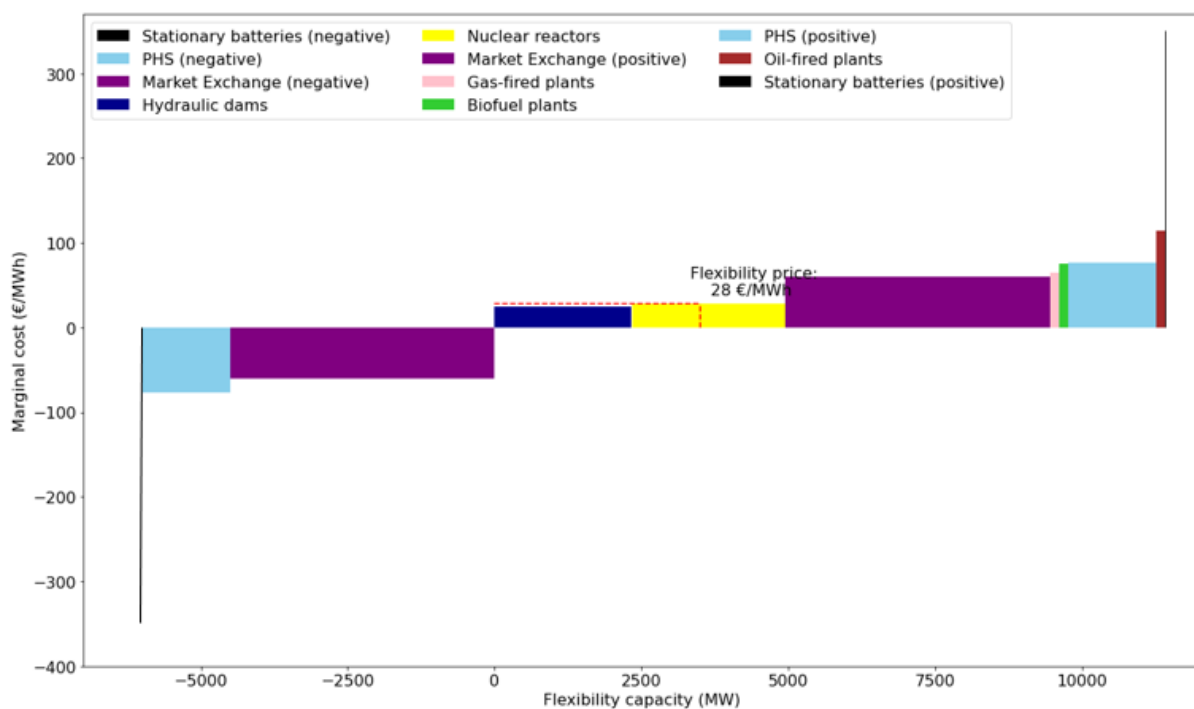


Figure 19 : Merit-order chart of the Occitanie flexibility mix in 2021 and marginal price when the flexibility demand is the one of a typical January afternoon of 2050, or 3 500 MW

## B. Periods with infeasible solving

We now have everything set up to run our model and obtain some results. In a first part, we want to determine if the current flexibility mix of region Occitanie is able to satisfy the three flexibility demands we have estimated for the year 2050. Thus, we run our model for each of the 17 520 periods contained in a full year of RL, and perform this operation for the three considered scenarios.

Once solved with the baseline calibration, the *Business-As-Usual* scenario contains no period with infeasible solving. This means that the totals of 11 430 MW of positive flexibility and 6 002 MW of negative flexibility are sufficient to cover the flexibility demand for every half-hour of the 2050 *Business-as-Usual* flexibility demand. Indeed, in this scenario, the maximum amount of required positive flexibility is 9 259 MW while the maximum of required negative flexibility is 3 595 MW, therefore, the already installed flexibility capacities are sufficient to satisfy the flexibility requirements estimated in this scenario. In other words, if the tendencies observed over the past years for electricity consumption and renewables deployment continue on the same path, the region does not require any additional investment in flexibility capacities until 2050, let alone investment realized to replace aging installations. This is an important result because it demonstrates that the region is already well equipped in flexibility capacities to support a continuous and moderate growth of electricity consumption and intermittent renewables capacities.

When running our optimization model for the 17 520 half-hours of our simulated 2050 REPOS RL, it appears that the cumulative sum of all local flexibility sources cannot be

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sufficient to serve the regional flexibility demand for 19.5% of the time. Said otherworldly, 19.5% of the time, the regional equilibrium between sources and demand of flexibility cannot be reached. As we see here, the regional perspective creates an opportunity for matching supply and demand for flexibility locally for more than 80% of the year, which come to enrich the traditional national scale approach as operational costs can be saved using the regional approach. As expected, these 3 789 periods are all ones with a negative flexibility demand that exceeds the 6 002 MW negative flexibility capacity constraint the Occitanie flexibility mix has currently. This result is important as it highlights that if no plan is prepared to face the challenges of a fast energy transition, the Occitanie power system will simply be not able to integrate the amounts of VRE capacities that are foreseen in the REPOS 2050 scenario. Either by increasing storage capacities, developing new transmission grid lines, or coupling the electricity and the transports sectors, the Occitanie region must already invest in flexible capacities, or else the power system will end up in a situation in which the regional management of flexibility cannot be ensured for almost a fifth of the year.

Finally, for the *Intensive Electrification* scenario, we find that our model ends up running with 3 819 periods with infeasible solving, or 21,8% of the time. This result is similar to the REPOS 2050 scenario one. This is due to the nature of the Residual Loads of the two scenarios, which are in fact quite similar in values, but not for the same reasons. In the REPOS scenario, a low consumption is present with a resolute but moderate increase in VRE capacities, which makes the residual load become negative for a significant amount of time. In the *Intensive Electrification* scenario, the negative RL is mostly due to the large VRE production resulting from the exploitation of 50% of the region's potential for renewables. Thus, the results end up being pretty similar meaning that in this scenario again, the region must invest in flexible capacities if it hopes to cope with the joint increase in electricity



consumption and intermittent renewable capacities. A sum up on infeasible periods is available in Appendix 2.B.

### C. Production curves

In this section, we aim to provide graphical views of the production curves of each flexible technology in each of the three scenario we have described before. From these figures, we can uncover how much each technology would be used in the different cases of flexibility demand we have projected for the year 2050. To keep our results consistent, we will now use only the periods with feasible solving, therefore we must discard around 20% of the REPOS and *Intensive Electrification* results. The motivation for this choice is two-fold. First, in this paper, we aim to focus on the regional level, hence we propose a methodology that only encompasses local sources of flexibility. The second reason, which follows on from the first, is that an optimization problem is deemed infeasible when all constraints cannot be satisfied by a solution. Therefore, if we only focus on regional flexibility management, and if the demand for flexibility exceeds the sum of all local capacities, then the constraint of equality between demand and supply cannot be satisfied. This results in the model providing inaccurate results for the concerned periods in which the aforementioned constraint cannot be satisfied. More precisely, when the solver of the PuLP<sup>28</sup> Python package we use to run the *Optimiflex* model encounters a situation where all constraints cannot be satisfied, it reacts by relaxing certain constraints, and in our case those constraints seem to be the target function of minimizing the cost, and the capacity constraint of stationary batteries, which are the first constraints declared in the code. In fact, to achieve a supply-demand balance for flexibility, the model suggests the intensive use of batteries as a solution. However, this does not respect

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<sup>28</sup> Available at <https://github.com/coin-or/pulp/issues/157>

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the logic of merit order, as batteries are the most expensive option for storage. Thus, we can't give much credence to the solutions found by the solver when the period is declared "infeasible". This is why we prefer to deem these periods managed at the national level and discard them from our analysis of regional equilibria.

The first case we present is the *Business-as-Usual* one, in which current trends of electricity consumption and renewables deployment are continued up to the year 2050. When we solve the baseline *Optimiflex* model with this flexibility demand, we obtain the following production curves for each flexible technology (see Figure 20).

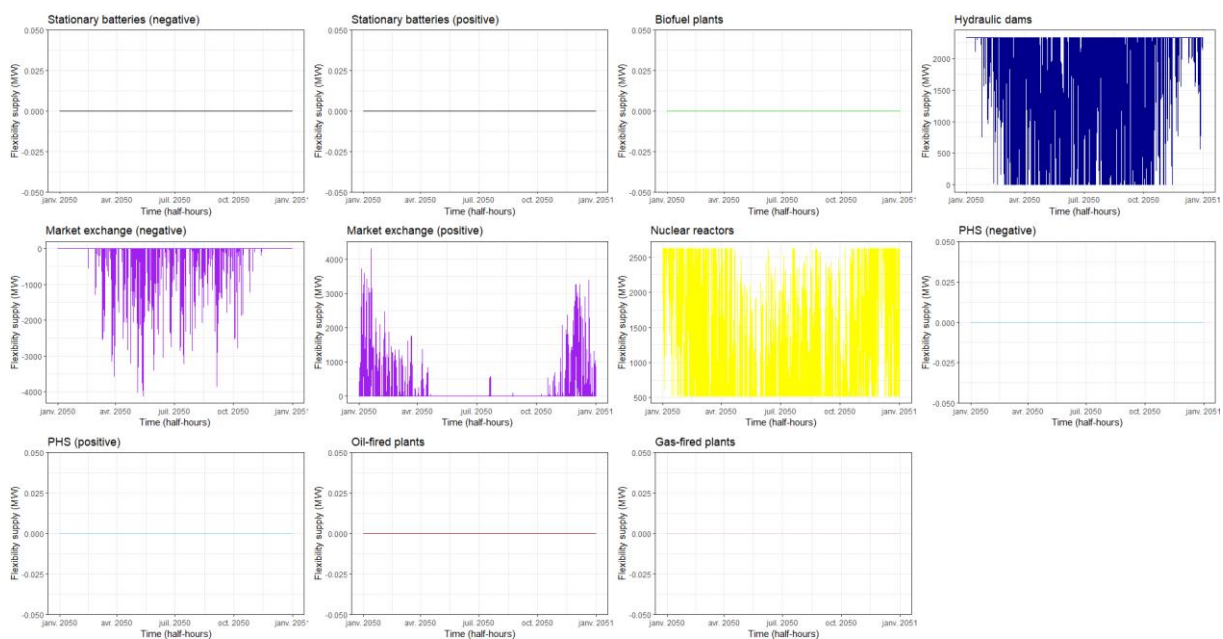


Figure 20 : Half-hourly generation curves of flexible technologies in the Business-as-Usual scenario with baseline parametrization

First and foremost, we can see on this graphical view that the only flexible technologies that are used in this scenario are the hydraulic dams, the nuclear reactors, and the

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market exchange in both ways. This reveals us that the current Occitanie flexibility mix heavily relies on costly and large-scale infrastructures. Thanks to economies of scale, these technologies are able to produce at a low marginal cost, which place them in the first positions in the merit-order built to satisfy the flexibility demand for every half-hour of the *Business-as-Usual* scenario. Due to its constraint of minimal production, the nuclear reactors technology is used 100% of the time but is also able to follow the variations of the flexibility demand in a *load-following mode* of functioning (see [Cany et al., 2016 ; Jenkins et al., 2018] for more details on this topic).

In the same way, the hydraulic dams, which are controllable units with the advantage of having already amortized infrastructures, follow the seasonal variation of the consumption and produce less during summer than in winter, where consumption is at its maximum. Finally, the market exchange technology is used to evacuate the excess electricity produced during summer which is mostly due to the more intense production of solar panels during this period. The market exchange technology is also used to buy the lacking electricity during peaks of demand, mostly in winter, when wind power can generate high amounts of energy, but not sufficient to cover the regional demand. Remember that VRE capacities are fixed in our scenarios, and that in our model, electricity trading prices are considered fixed because of we lack historical prices data, but also because we don't aim to model 2050 prices as there are more than uncertain, which leads to a fixed place of the market exchange technology in the merit-order. Future work could be implemented to investigate the price sensitivity of the baseline merit-order to the variations of electricity trading prices. Overall, our results reflect in general the way a decarbonated power system in region Occitanie would work. The current power mix seems to provide enough flexibility to introduce renewables at the rate we have known so far.

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In the REPOS 2050 case, the load curves of the various flexible technologies are different. Indeed, in this scenario, intermittent renewables capacities are more significant than in the *Business-as-Usual* scenario, and the increase in electricity consumption due to societal and technological changes are compensated by intense efforts of energy efficiency.

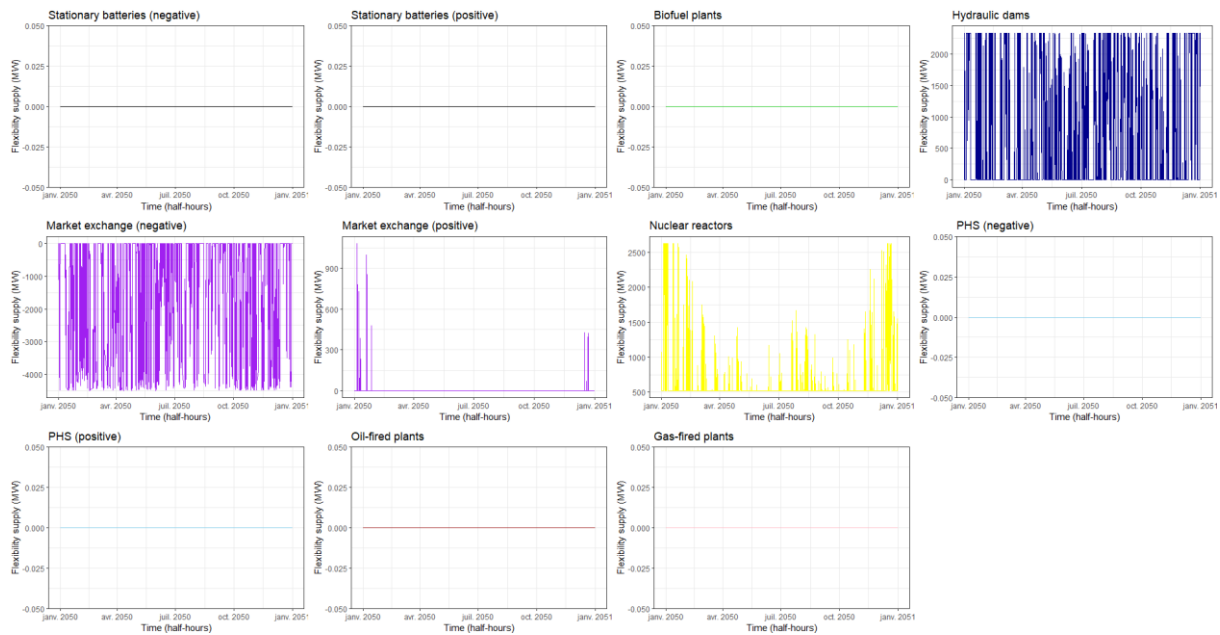


Figure 21 : Half-hourly production curves of flexible technologies in the REPOS 2050 scenario with baseline parametrization

In this case, we observe the same dominating flexible technologies, but in rather different proportions. Here, the production of hydraulic dams is more variable and does not follow a typical seasonal pattern. However, this cyclical pattern is reflected in the production of nuclear reactors, which higher their production during winter and lower it during summer. The positive Market Exchange option is almost never used, as the flexibility demand level is

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lower in this scenario (-479 MW in average). Overall, it is the negative Market Exchange flexibility option that is used most of the time in order to evacuate towards the national grid the surplus electricity produced by intermittent renewables installed in Occitanie. This tells us that in the absence of significant storage capabilities, if the region follows the REPOS 2050 path, it will rely even more on the grid capabilities than it does nowadays in the absence of new investments in local flexibilities. The positive-energy balance goal seems to be attained in this scenario, but in a proportion that will most probably require investments in storage or grid capabilities. Here, we want to underline the importance of storage, which is never used in this scenario but could become a determinant factor to absorb the huge amount of electricity produced by renewables in cases in which the grid cannot. Indeed, another limitation of our simulation is that there is no actual demand for the excess electricity sold via the Market Exchange option. We consider in our model that the shift towards renewables is not evenly spread among the French territory and that, Occitanie, with its significant potentials in wind and sun, becomes an actual producing region and supplies other regions with lower potentials such as Auvergne-Rhône-Alpes or Nouvelle Aquitaine. Here again, electricity price fluctuations are not taken into account, but could also become an incentive to invest in storage technologies.

Finally, we now want to display in a graphical manner how the flexibility technologies serve the demand in the *Intensive Electrification* scenario (see Figure 8). Remember that in this scenario, new uses, and a general shift towards electricity as the dominant energy carrier end up in significant increases in both electricity consumption and intermittent renewables capacities. The main difference with the REPOS scenario is that here, efforts in energy efficiency do not compensate the increase in electricity consumption, which leads the regional power system to be forced to exploit almost half of its renewables potential.

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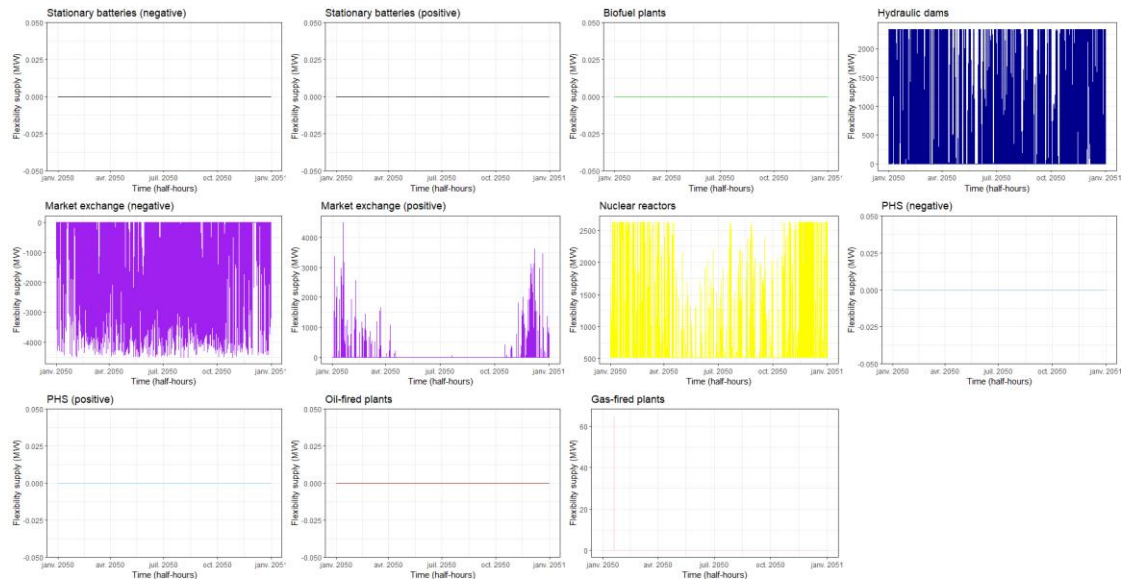


Figure 22 : Half-hourly generation curves of flexible technologies in the Intensive Electrification scenario with baseline parametrization

The *Intensive Electrification* load curves of the different flexible technologies appear to be rather similar to the REPOS ones. Indeed, these two scenarios describe to rather similar situations for the Occitanie power system, with a notable difference in the levels of electricity consumption and renewable production. Therefore, we observe on this load curves chart that the dominant flexible technologies that are the hydraulic dams, the nuclear reactors and the market exchange are called in higher proportions than in the REPOS scenario. This is due to the higher production of solar PV and the higher consumption level observed during peak load times. Thus, nuclear reactors are called at their maximal capacity a significant amount of time, when positive market exchange and even gas fired plants are called to supply the peak winter load. Overall, the conclusion we can extract from these results is the similar as the two other scenarios: the Occitanie power system strongly relies on large scale and low marginal cost technologies, is subject to price fluctuations, and requires more negative flexibility capacities to absorb all the surplus electricity produced by renewables, especially solar PV.

## D. Cost of flexibility

As the objective function of our model is to minimize the total cost of supplying flexibility to the system, we now want to present the half-hourly total cost results we gathered from the three simulations.

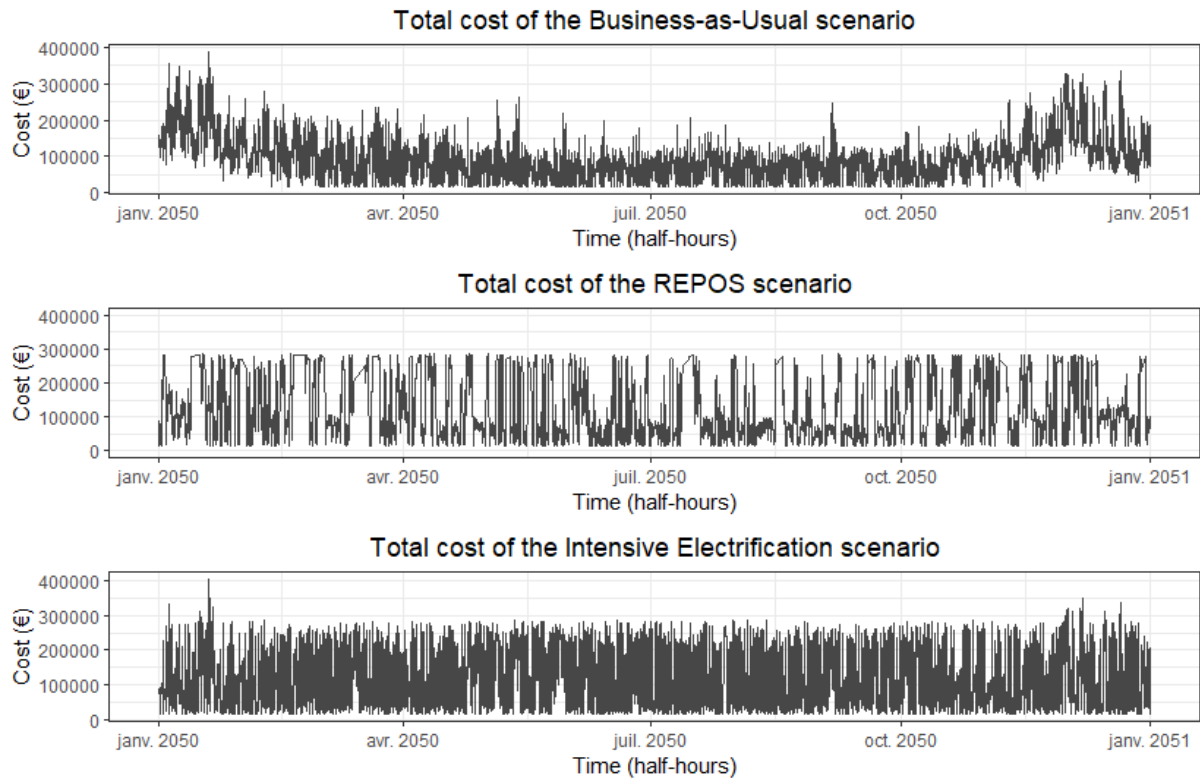


Figure 23 : Half-hourly total costs of the three considered scenarios with baseline parametrization

Series	Mean	St. Dev.	Med.	Min	Max	1 <sup>st</sup> Qu.	3 <sup>rd</sup> Qu.
<b>Total Cost</b>							
<i>Business-as-Usual</i>	97 236	64 167	81 021	14 672	406 010	49 097	126 892
<b>Total Cost REPOS</b>							
2050	99 234	69 523	73 629	14 672	284 672	48 597	135 962
<b>Total Cost Intensive</b>							
<i>Electrification</i>	95 759	55 084	87 013	14 672	389 905	57 747	119 220

Table 10 : Descriptive statistics of half-hourly Total Costs series in €/MW for the three considered scenarios with baseline parametrization

This chart and table allow us to compare the optimization target value for each of the three considered scenarios. First, we can observe on the time series associated with the total cost of the *Business-as-Usual* application that the total cost follows a trajectory similar as the residual load of this scenario. Said otherworldly, the total cost appears here to be a regular function of the flexibility demand. However, in the two other scenarios, the function linking the total cost to the residual load seems to be rather more complex. Another interesting result is that the scenario with the lesser cost volatility is also the one with the lowest mean total cost: it is the *Intensive Electrification* scenario. In the same way, the total cost of the REPOS 2050 scenario is the highest in mean and also the most volatile. One can see here that there might exist a relationship between the volatility of the simulation target variable results and its mean level. Finally, we can see that the maximum total cost value is attained in the *Business-as-Usual* scenario, which seems rather unexpected as it is not in this scenario that we find the highest Residual Load value. However, recall that the results of the REPOS and *Intensive Electrification* are here reduced by around 20% in size and that the infeasible solving results might very well affect the distribution of total costs among these scenarios if they would be considered. That being said, we already mentioned upper in the text that our aim here is to focus on the regional capability to manage its own flexibility requirements, and that these results have a low, if inexistant meaning from an energy-economics point of view.

## 4. Sensitivity analyses

In the previous section, we have gathered results about the capacity of the current Occitanie flexibility mix to respond to various projected flexibility demands. To continue our exploration, we propose in this section to perform sensitivity analyses on four flexibility



technologies that are critical for the future of the Occitanie power system: nuclear reactors, hydraulic dams, stationary batteries, and fossil-fueled plants. Indeed, the capacities and marginal costs of these technologies are very likely to change within the next decades, thus we want to provide an analysis that includes these potential changes.

### A. The *Nuclear interruption* variant

Due to their low marginal-cost, high production capacity and longevity (around 40 to 60 years), nuclear reactors have been the backbone of the French power system for several decades. In recent years, nuclear reactors have been also used in a *load-following* mode to accommodate the introduction of variable and renewable production capacities. However, the French nuclear reactors fleet is ageing, and this is also the case for the only nuclear power plant installed in Golfech, north-west Occitanie. This nuclear plant was first operated in 1990 and thus will reach its maximal longevity around the year 2050. Therefore, it becomes interesting to investigate the way the flexibility mix would be operated without having access to the nuclear reactors technology. In this variant, we will simply remove the nuclear reactors technology from the flexibility mix and keep the costs and capacities of the rest of the technologies the same. This will provide us with load curves and costs results that will most probably be different from the baseline case, in which a large share of positive flexibility requirements was supplied by the nuclear reactors. But first, let us present the shape of the merit-order in this case.

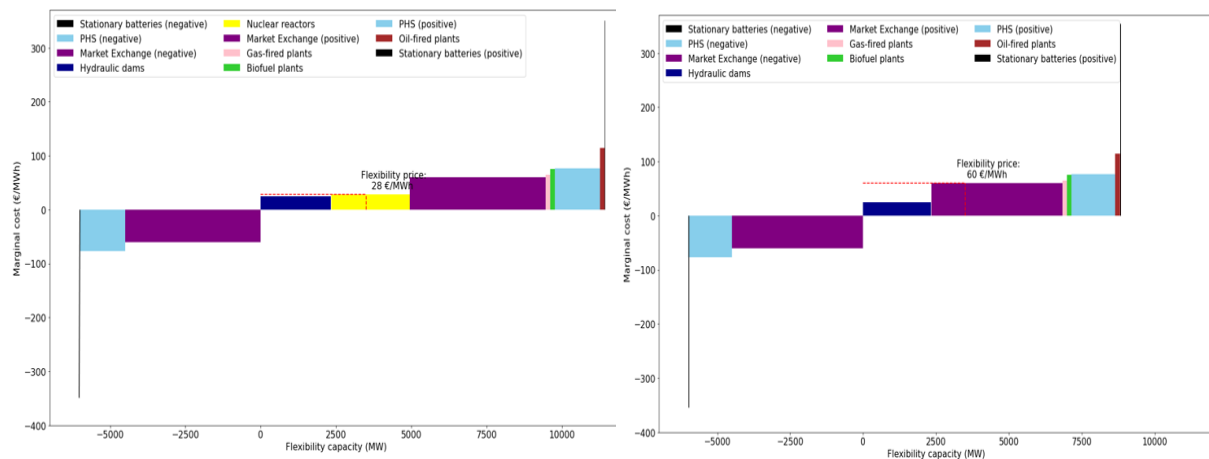


Figure 24 : Flexibility merit-order of the Occitanie power system in the *Nuclear Interruption* variant (left), compared with the baseline parametrization merit order (right), with a flexibility demand set to the one of a typical January afternoon of 2050, or 3 500 MW

Without nuclear reactors, the total capacity of the Occitanie flexibility mix is 8 810 MW, which represents a reduction of around 20% of the initial total capacity. Positive flexibility technologies are all move left on the merit-order, while hydraulic dams keep its first position in the positive side on the flexibility merit-order. The resulting equilibrium price for a typical afternoon of January is set to 60 €/MWh which corresponds to the marginal cost of the Market Exchange technology, i.e., the flexibility price would be in this case set externally. Once again remember that we have chosen to keep a fixed averaged yearly price for this technology. This poses the question of the flexibility demand elasticity to changes in prices. Here, we want to emphasize that the operational matching of supply and demand is so necessary for the grid to function well that we must make the hypothesis that the price elasticity is null. This means that the flexibility demand does not react to changes in price. Finally, we could say that the estimated maximum price to which the flexibility demand would react is equivalent to the value of lost load, which on European markets oscillates between 1 500 and 22 940 €/MWh according to [Swinand et al., 2019].

We then solve our *Optimiflex* model for all 17 520 half-hours of the three projected flexibility demands. This time, we end-up with 4 infeasible periods for the *Business-as-Usual* scenario. Indeed, there are 4 periods during which the Residual Load is at such level that all the cumulated capacity of the flexibility mix (without nuclear reactors this time) cannot satisfy it. These four periods can easily be anticipated with a proper Residual Load forecasting technique, see chapter 1 of this thesis. This reveals us that even without the help of nuclear reactors, the system can cope with regular increases of both electricity consumption and renewable capacities. Another interesting result is that in the REPOS 2050 scenario, which envisions a reduction of the electricity consumption and a significant increase in renewable capacities, the *Nuclear Interruption* parametrization end up with 3 044 periods with infeasible solving, or 17.4% of the time, which is around 4% less than in the baseline parametrization.<sup>29</sup> This result is explained by the fact that the nuclear reactors have a minimal capacity at which they can function, which actually increases the need for negative flexibility in times of high renewable production and low consumption. We also find a similar result for the *Intensive Electrification* scenario, in which the *Nuclear Interruption* parametrization end up with 3 461 periods with infeasible solving, which represents 19.8% of the time, or 2% less than in the baseline parametrization. Remember that all these infeasible results can be found in Appendix B.

The production curves also appear to be highly different with this *Nuclear Interruption* parametrization (see Appendix 2.C for graphical representations). When nuclear production lacks, conventional generation (Biofuel plants, Oil-fired plants, and Gas-fired plants) as well

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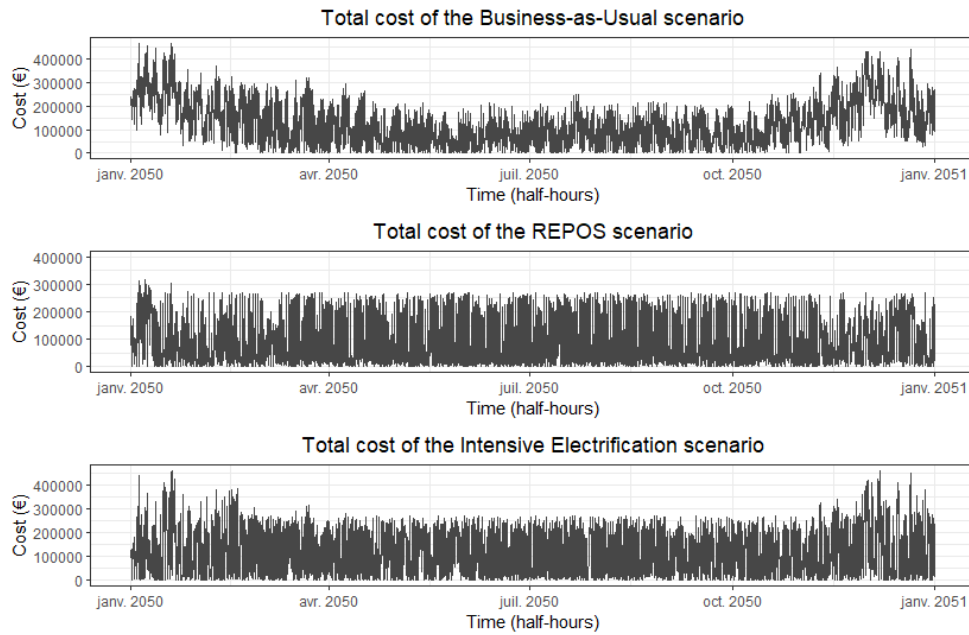
<sup>29</sup> Note that the infeasible periods result of each scenario and parametrization can be found in Table 7 in appendix B.

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as positive Pumped Hydro Storage are called to satisfy the positive flexibility requirements in the *Business-as-Usual* scenario. Also, both the Hydraulic dams and Market Exchange follow the shape of the Residual Load curve. In the REPOS 2050 scenario however, only the Market Exchange and Hydraulic dams flexibility options are called. They are often used at their maximal capacity though. It is also the case in the *Intensive Electrification* scenario, but this time conventional generation and even negative Pumped Hydro Storage are used to cover the flexibility requirements.

Logically, the total costs of the three considered scenarios are also affected by the lack of nuclear option. In average, the total cost increase in both the *Business-as-Usual* and the *Intensive Electrification* scenarios, which both have high positive flexibility requirements levels. The variability of these total cost also increased significantly. An unexpected result is that the average total cost of the REPOS 2050 scenario actually decreased, as well as its variability, which tells us that in a future without nuclear power, under the bold hypotheses of the REPOS scenario, reducing the consumption and opting for renewables might be the most cost-efficient solution.

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Figure 25 : Half-hourly total costs of the three considered scenarios with *Nuclear Interruption* parametrization

Series	Mean	St. Dev.	Med.	Min	Max	1 <sup>st</sup> Qu.	3 <sup>rd</sup> Qu.
<b>Total Cost</b>							
<i>Business-as-Usual</i>	124 254	87 348	111 465	0	468 695	51 115	179 025
<b>Total Cost REPOS</b>							
2050	77 207	66 669	52 025	0	314 385	28 923	110 745
<b>Total Cost <i>Intensive</i></b>							
<i>Electrification</i>	105 019	83 756	83 085	0	460 659	37 350	158 276

Table 11 : Descriptive statistics of half-hourly Total Costs series for the three considered scenarios with *Nuclear Interruption* parametrization

## B. The *Constrained hydropower* variant

In this new variant, we aim to explore how climate change could affect the available hydropower capacities of region Occitanie. Already during summer 2022, a severe draught has reduced the amount of available water in neighboring regions such as Provence-Alpes-Côte d'Azur. Thus, the impact of climate change on hydropower availability is a growing

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concern in many regions of the world, including Occitanie. Indeed, climate change involves changes in precipitation patterns, temperature and river flows that can impact the capacity of both run-of-the-river and high-water hydropower facilities to generate electricity. As a consequence, both baseload and peak electricity production can be affected by these changes in hydraulic resource availability.

Several studies [Bernard Lehner et al., 2005; Denis Ruelland et al., 2015; Ying Meng et al., 2020; Camille Labrousse, 2021] have found that climate change could potentially lead to a reduction in hydropower potential across Europe. Even more precisely, Anthony Lemoine, in his 2021 thesis, has developed a set of indicators for characterizing the risk that climate change represents on hydroelectric resources [Anthony Lemoine, 2021]. On the reservoirs studied, Lemoine finds that the loss of annual hydropower production could be somewhere between -1.5% and 18.9% depending on the climate change scenario retained. Therefore, in this section, we will reduce the available capacity of hydropower dams by a central value taken between what has been proposed by Lemoine, i.e., reducing by 10% their availability, and see how the flexibility management is affected by this reduction. This reduction only slightly affects the flexibility merit-order we have presented before, as shown on Figure 26. Indeed, the merit-order only slightly moves to the left as the capacity offered by the hydraulic dams is reduced by a factor 0.9. This overall positive flexibility capacity of this newly considered system is 11 196 MW, which still represents more than 98% of this initial flexibility mix. Overall, the system has simply lost around 234 MW of capacity, which should not affect much the shapes of the load curves in each of the three flexibility demand scenarios considered.

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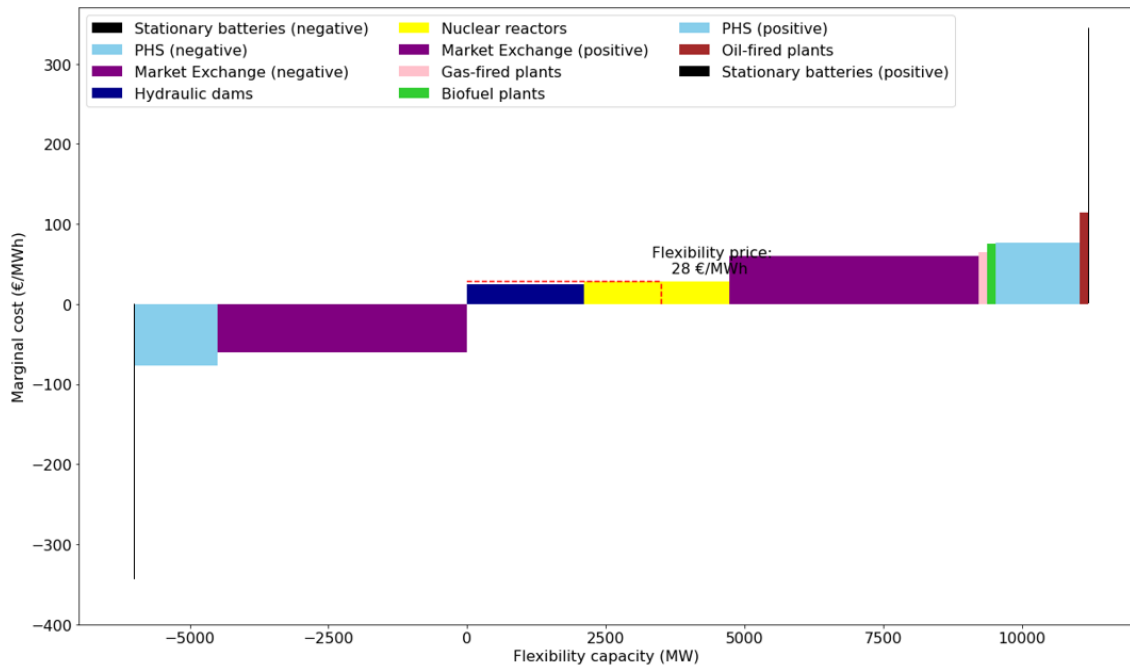


Figure 26 : Flexibility merit-order of the Occitanie power system in the *Constrained Hydropower* variant, with a flexibility demand set to the one of a typical January afternoon of 2050, or 3 500 MW

When we solve the three considered scenarios with the *Constrained Hydropower* parametrization, the results appear to be quite similar to the Baseline results. Indeed, in terms of feasibility, the results show that the reduction in hydropower capacity only slightly affects the feasibility of the flexibility management. In the Business-As-Usual scenario, the system is optimal 100% of the time. In the REPOS scenario, 3 789 periods are infeasible, which represents 21,6% of the total periods. In the *Intensive Electrification* scenario, 3 820 periods are infeasible, which represents 21.8% of the total periods.

Thus, as the production curves and total costs results remain quite similar to the Baseline scenario (see Appendix 2.D), we can only provide the same conclusion that is these infeasible periods highlight the need for the power system to have alternative sources of flexibility to ensure system stability and reliability. This could include, for example, energy storage systems, demand-side management, or interconnections with the national grid. It is

also important to consider the potential impact of climate change on hydropower capacity in the planning and operation of power systems to ensure that the system remains flexible and reliable in the future.

### C. Exploring the criticalness of battery storage: the *Battery Development* variant

The cost of batteries has been decreasing rapidly over the past years. According to the International Renewable Energy Agency (IRENA), the cost of lithium-ion battery packs has fallen by approximately 85% between 2010 and 2018 [IRENA, 2019]. This trend is expected to continue, driven by technological advancements, increased production capacity, and economies of scale [Oliver Schmidt et al., 2017]. A study by Nykvist and Nilsson projects that battery the marginal cost could decrease from 350€/MWh to around \$100 per kWh by 2030 [Nykvist et al., 2015]. More recent estimates from BloombergNEF (2021) predict that the average cost of lithium-ion battery packs could fall below \$100 per kWh by 2024, with some manufacturers achieving even lower costs [Bloomberg, 2021].

The decline in battery costs is likely to make battery storage more economically viable and competitive with other flexibility options, such as pumped hydro storage or CCGT plants. In their analysis, Kittner et al. demonstrate that the decreasing costs of energy storage technologies, including batteries, could contribute to the accelerated deployment of renewable energy sources, thereby fostering the transition to a low-carbon energy system [Kitner et al., 2017].



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It is worth mentioning that we consider in our model Lithium-ion batteries as they are currently the most popular choice for grid-scale energy storage, due to their high energy density, fast charging and discharging capabilities, and decreasing costs.

However, predicting the exact marginal cost of lithium-ion batteries by 2050 is challenging due to various factors, including technological advancements, manufacturing scale, and market dynamics. Still, based on the current trends and available research, we can make an educated projection for the marginal cost of lithium-ion batteries by 2050. Here again, we want to emphasize that the actual means of storage represented by the Vehicle-to-Grid option could very well affect the overall cost and technology development of lithium-ion batteries.

A study by Kavlak et al. estimates that the cost of lithium-ion batteries could decline by an additional 50% between 2018 and 2030, reaching around \$50 per kWh [Kavlak et al., 2018]. Considering this trend, it's reasonable to assume that by 2050, the marginal cost of lithium-ion batteries could be substantially lower than \$50 per kWh. Additionally, improvements in battery performance, such as increased energy density, longer cycle life, and faster charging and discharging rates, could further contribute to lowering the Levelized Cost of Storage (LCOS) of stationary batteries by 2050. Based on these assumptions, and taking into account operation and maintenance costs, we can estimate the value of the LCOS of lithium-ion batteries for 2050 being around 60€/MWh. This marginal cost can seem to be optimistic with regards to the availability of primary resources needed to build batteries, such as lithium. However, recent discoveries of lithium resources around the globe let us think that this barrier could be overcome and to that the price of lithium over time will be relatively stable.

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Having said this, we propose then to consider a significant increase in battery storage capacity in Occitanie by 2050. To reflect the regional commitment to renewable energy development and the recognition of the importance of energy storage in facilitating a low-carbon energy transition, we propose a target of 500 MW of battery storage by 2050. This would require continued investment in energy storage technologies, supportive policies and regulations, and ongoing innovation to further reduce the costs of batteries and improve their performance, but we consider this assumption acceptable with regards to the energy transition happening fast in France and especially Occitanie.

We now solve our *Optimiflex* model with this *Battery Development* parametrization variant. The merit-order curve is affected by the 498 MW of additional battery storage capacity, with a marginal cost that is close to the Market Exchange flexibility option. The merit-order curve thus incorporates both negative and positive flexibility capacities for the Battery Storage option (see Figure 27).

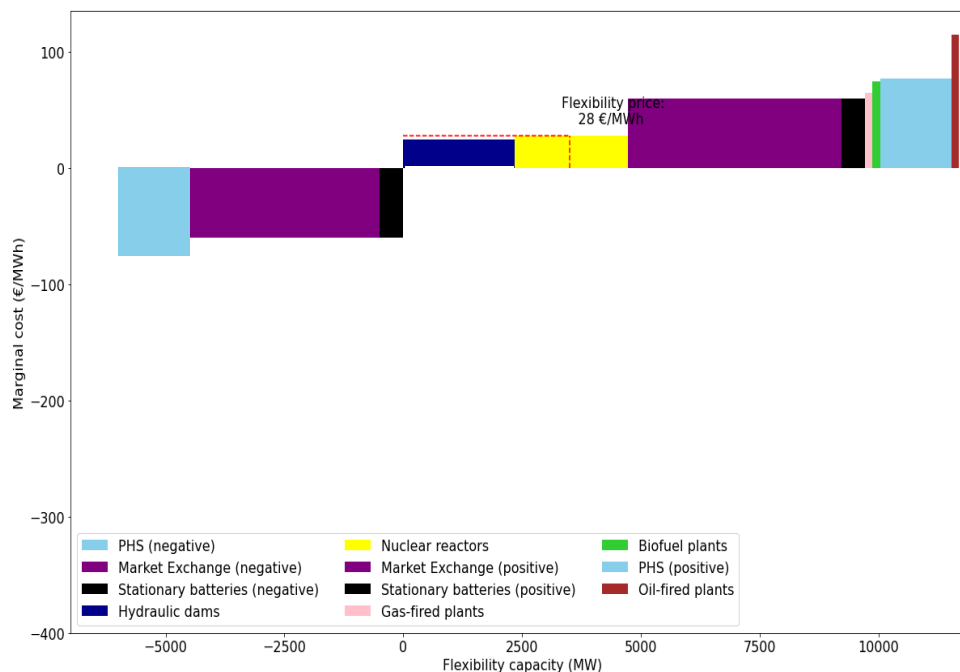


Figure 27 : Flexibility merit-order of the Occitanie power system in the *Battery Development* variant, with a flexibility demand set to the one of a typical January afternoon of 2050, or 3 500 MW

When we solve the model for the 17 520 periods of the three considered scenarios, we end up having the following results in terms of number of infeasible periods. With this parametrization, the *Business-as-Usual* scenario is solved with 100% optimality, while the REPOS scenario presents 3 412 infeasible periods, or 19.47% of the time, which is lower than the *Constrained Hydropower* parametrization, but higher than in the *Nuclear Interruption* one. Finally, the Intensive Electrification scenario is solved with 3 808 infeasible periods, or 21.74% of the time which is similar to the *Constrained Hydropower* parametrization. We could have expected that the development of storage capabilities would have reduce the number of periods in which the regional equilibrium cannot be solved. However, due to the variability of tested RLs, a capacity of 500 MW of additional storage seems to be very low compared to the actual flexibility requirements. For the rest of the paper, we consider only feasible results for both the REPOS and Intensive Electrifications scenarios. The main result we can get from this parametrization is an increased usage of stationary batteries which provide quite often their full discharge capacity in the three considered scenarios (See Appendix 2.E). In terms of cost, the three scenarios present a total cost average significantly lower than in the Nuclear Interruption parametrization, as well as in the Baseline and Constrained Hydropower parametrizations. This demonstrates the potential of battery storage to bring significant shares of flexibility at a reasonable cost if the proposed assumptions are realized.

Series	Mean	St. Dev.	Med.	Min	Max	1 <sup>st</sup> Qu.	3 <sup>rd</sup> Qu.
Total Cost <i>Business-as-Usual</i>	95 759	55 084	87 013	14 672	389 905	57 747	119 220
Total Cost REPOS 2050	77 673	66 669	59 312	14 672	314 385	37 532	110 745
Total Cost <i>Intensive Electrification</i>	105 019	83 756	83 085	0	460 659	37 350	158 276

Table 12 : Descriptive statistics of half-hourly Total Costs series for the three considered scenarios with *Battery Development* parametrization

#### D. Going CO<sub>2</sub> neutral: the *Fossil fuels exclusion* variant

In this final variant, we want to acknowledge that providing flexibility to the grid to support the inclusion of renewables is possible with only CO<sub>2</sub>-neutral technologies. Thus, we will test here our *Optimiflex* model with a parametrization in which capacities of Gas-fired and Oil-fired plants are set to zero. Note that they only represent 2.7% of the overall flexible capacity of the current Occitanie power system. The expected outcome of this experiment is to assess whether these technologies are necessary to support the flexibility mix of Occitanie region in the three considered scenarios. Such analysis could be useful in the sense that it would be an additional argument to support CO<sub>2</sub> emissions regulation, which itself is compulsory to achieve climate goals set by the Paris Agreement. Without fossil fueled plants, the flexibility merit order of region Occitanie has the following shape:

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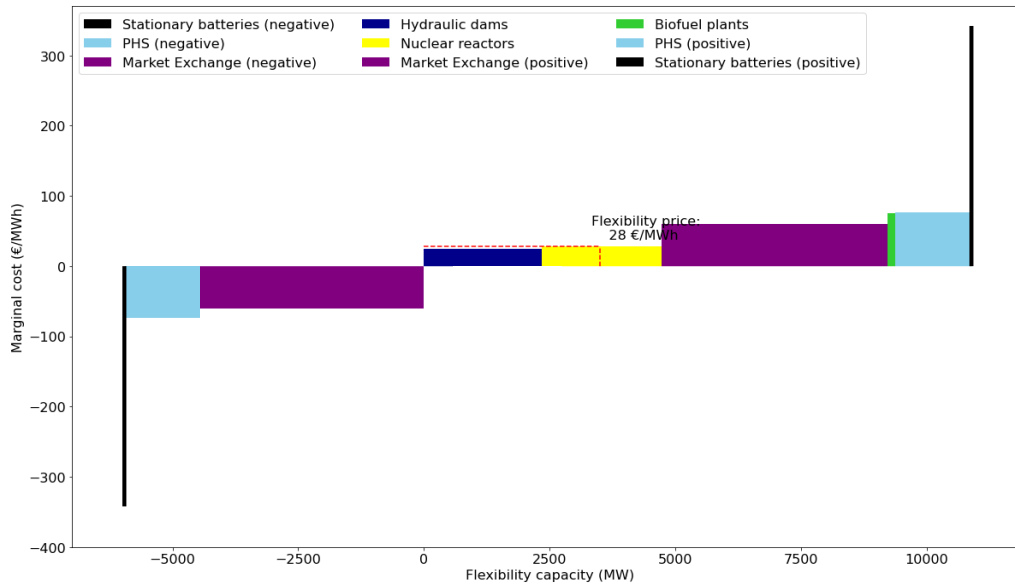


Figure 28 : Flexibility merit-order of the Occitanie power system in the *Fossil fuels exclusion* variant, with a flexibility demand set to the one of a typical January afternoon of 2050, or 3 500 MW

Solving our *Optimiflex* model for our three considered scenarios with the *Fossil Fuels Exclusion* parametrization ends up with very similar results to the *Battery Development* parametrization. Indeed, here again, the Business-As-Usual scenario is solved with an optimal solution 100% of the time, while the REPOS and Intensive Electrification are solved with respectively 19.48% and 21.80% of infeasible solutions. Here again, we will consider only the optimal resolutions in further calculations.

The shape of the load curves for this parametrization is again very similar to the *Battery Development* parametrization, see Appendix F. It is an expected results that the flexibility mix is dominated by Hydropower, Market Exchange and Nuclear technologies, as they are in this case the most cost efficient. On a final note, we can compare the cost of the *Battery Development* and *Fossil Fuels Exclusion* parametrizations by noting that they are also very similar. The main difference is for the *Intensive Electrification* scenario which has a

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lower mean and less variable total cost. This configuration underlines the fact that without fossil-fueled technologies and with a strong development of battery technology, the flexibility mix would remain pretty much the same. It is worth noting that in the two cases, the *Business-as-Usual* scenario is solved in the same manner, meaning that if the trajectory of consumption and VRE development remains the same as what we observed over the ten past years, the flexibility management of Occitanie power system can be achieved without the help of fossil-fueled technologies. One can also imagine that the future cost of fossil-fuels will be so prohibitive, if it encompasses a carbon valuation, that these technologies will anyway be not used before 2050.

Series	Mean	St. Dev.	Med.	Min	Max	1 <sup>st</sup> Qu.	3 <sup>rd</sup> Qu.
Total Cost <i>Business-as-Usual</i>	95 759	55 084	87 013	14 672	389 905	57 747	119 220
Total Cost REPOS 2050	77 673	58 930	59 312	14 672	284 672	37 532	94 727
Total Cost <i>Intensive Electrification</i>	97 236	64 167	81 021	14 672	406 660	49 097	126 832

Table 13 : Descriptive statistics of half-hourly Total Costs series for the three considered scenarios with *Fossil Fuels Exclusion* parametrization

## 5. Conclusion

To conclude, our study emphasizes the importance of understanding and addressing the flexibility needs in decarbonized power systems, specifically using the Occitanie region of South France as a case study. As the global energy landscape shifts towards a sustainable, low-carbon future, power systems must adapt to accommodate the increasing penetration of Variable and Renewable Energies (VRE). Achieving this goal requires a comprehensive understanding of the challenges and potential solutions, which this study aims to provide.

Through the creation of multiple scenarios and the application of a merit-order based optimization model, we have highlighted the necessity for significant investments in flexible capacities by 2050. Our findings indicate that hydropower, nuclear, and market-based technologies will play a crucial role in supporting the integration of VRE capacities into the power system, ensuring a stable balance of supply and demand. By examining three different variants of the Residual Load (RL) function, we have uncovered several paths that the flexibility mix could take, offering valuable insights for decision-makers.

Another important result is that for the REPOS 2050 and *Intensive Electrification* scenarios, the current flexibility mix of Occitanie region can simply not satisfy the projected flexibility requirements for around 20% of the time. In other words, the flexibility requirements exceed the overall flexibility capacity of Occitanie region for a significant number of periods of time. More precisely, it is the negative flexibility requirements, induced by the high shares of intermittent renewables introduced into the generation mix in these scenarios, that cannot be satisfied for these identified periods. The day-night variability of solar is the most significant factor contributing to the high variability of the residual load curves in these two scenarios.

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Moreover, our sensitivity analyses offer valuable insights into the potential outcomes that may impact the provision of flexibility in the future Occitanie power system. These analyses highlight the importance of considering various factors and uncertainties when planning for future energy infrastructure investments. For instance, availability of flexible resources, technological advancements, or even changes in energy policies can significantly impact the optimal flexibility mix. More precisely, with the help of our model and its variants, we have demonstrated that the decommissioning of nuclear power could end up in a reduction of flexibility cost for the most ambitious scenarios such as the REPOS 2050. We have also shown that the balance between supply and demand of electricity can be achieved without the help of carbon-intensive technologies such as gas or oil-fired plants. On a final note, our projections suggest that hydropower availability reduction due to climate change may not affect much the flexibility equilibrium at the 2050 horizon.

In light of these findings, it is essential for policymakers, industry stakeholders, and researchers to work collaboratively to develop innovative solutions and strategic investment plans. These efforts will help address the flexibility challenges posed by the increasing penetration of VRE in power systems, ensuring a secure and reliable supply of electricity as we transition towards decarbonization. To achieve this, continuous dialogue between various stakeholders is vital to foster a collective understanding of the challenges and potential solutions, ensuring that the developed strategies are well-informed and effective.

Additionally, the methodologies and insights gained from this case study can be applied to other regions and countries with similar goals of decarbonization and increased renewable energy adoption. As the world moves towards a more sustainable energy future, sharing knowledge and best practices across borders will be crucial in accelerating the global transition and overcoming common challenges.



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Ultimately, our study underlines the importance of a proactive approach in planning for the future of power systems, taking into account the complex interplay between VRE integration, flexible capacity investments, and the uncertainties of future electricity consumption patterns. This approach will be crucial in supporting the global transition towards a more sustainable and low-carbon energy future.

To ensure long-term success, it is crucial to continually monitor and evaluate the effectiveness of implemented strategies and adapt them as needed. As new information and technologies become available, it is essential to reassess the assumptions and methods used in planning and decision-making. This iterative approach will help maintain the relevance and effectiveness of the strategies and policies in place, enabling power systems to thrive in a rapidly changing energy landscape.

Finally, we want to emphasize that the regional point of view adopted in this paper is definitely dependent on the national or supranational grid. Our results demonstrate that for around 20% of the time, ambitious scenarios such as the REPOS 2050 and *Intensive Electrification* completely rely on the grid-scale infrastructures to achieve the supply-demand equilibrium. This underlines the fact that the national grid as well as investments in grid capacities are crucial for the integration of VREs within regional power systems. While some flexibility needs can be managed on a local scale to better integrate intermittent energy sources and local sources of flexibility, it is crucial to maintain and develop the relationship between regional and national, or even supranational, power systems.

In summary, this study contributes valuable insights and methodologies for understanding and addressing the flexibility needs of decarbonized power systems. By analyzing the case of the Occitanie region, we have demonstrated the significance of investments in flexible capacities and the importance of a proactive and adaptive approach in planning for the future of power systems. Further studies should also explore the demand side

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flexibility which will be determinant to achieve the energy transition. Indeed, in this study we only have focused on the supply side, but sound incentives, new technologies and new market products can be useful tools to achieve demand-side flexibility, either at the industrial scale or the residential level.



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# CONCLUSION GENERALE

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## 1. Résumé des principaux résultats

### A. Introduction au principaux résultats

Avec la transition énergétique actuelle, un nouveau paradigme pour la production d'électricité émerge. Des parts croissantes d'Énergies Renouvelables Variables (VRE) telles que le solaire photovoltaïque (PV) et l'éolien sont intégrées dans les systèmes énergétiques, et leur nature décentralisée invite à repenser la manière dont les systèmes énergétiques sont conçus et gérés. La flexibilité, ou la capacité d'un système énergétique donné à faire face rapidement et efficacement à des changements dans la demande ou la production, devient une question cruciale qui nécessite de nouvelles approches pour être abordée. En effet, l'impératif double de maintenir la sécurité énergétique tout en progressant vers la décarbonation place la flexibilité des systèmes électriques au premier plan de nos efforts collectifs pour forger des systèmes énergétiques durables. Ainsi, au cœur de cette thèse se trouve une question qui encapsule les défis et opportunités associés à l'essor des VRE et leur impact sur la gestion de la flexibilité : Comment gérer au niveau régional les besoins de flexibilité induits par l'essor des VRE ? Cette enquête est particulièrement opportune, se déroulant dans un contexte mondial où les impératifs du changement climatique, soulignés par l'Accord de Paris, nous obligent à repenser notre infrastructure énergétique.

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Cette recherche trace une nouvelle trajectoire en examinant l'ascension croissante des sources d'énergie intermittentes, telles que le solaire et l'éolien, qui sont intrinsèquement décentralisées. Ce changement souligne un besoin fondamental de réévaluer et de reconfigurer les cadres traditionnellement centralisés des systèmes énergétiques nationaux (ou supranationaux). L'argument développé ici repose sur la logique qu'une approche régionale devient de plus en plus pertinente et efficace pour relever les défis de la flexibilité des systèmes énergétiques. Contrairement aux modèles centralisés, les systèmes régionaux sont mieux adaptés pour intégrer la nature décentralisée des sources modernes d'énergie renouvelable, puisqu'ils peuvent débloquer le potentiel des sources de flexibilité locales de manière plus rentable et avec un degré de précision plus élevé. Ils offrent un cadre plus adapté, réactif et agile pour gérer la variabilité et l'incertitude introduites par ces sources d'énergie intermittentes. En se concentrant sur les systèmes énergétiques régionaux, cette étude vise à éclairer comment une gestion et une prise de décision régionalisées peuvent exploiter plus efficacement le potentiel des VRE, améliorant ainsi la flexibilité et la fiabilité globales du système dans une ère marquée par un changement significatif vers des solutions énergétiques durables. Utilisant des techniques de prévision sophistiquées, développant un modèle d'optimisation et menant une analyse approfondie des scénarios, cette thèse fournit un examen détaillé de la manière dont un système électrique régional peut gérer habilement la variabilité des VRE.

L'Occitanie sert de cas d'étude idéal pour la flexibilité des systèmes électriques en raison de son intégration significative de sources d'énergie renouvelable, de son mix énergétique diversifié et de ses politiques énergétiques régionales uniques, offrant des perspectives précieuses sur la gestion de la flexibilité dans un paysage énergétique renouvelable en rapide évolution. C'est également très intéressant en raison de son plan énergétique régional nommé

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REPOS 2050, qui envisage une augmentation significative de la part des VRE parmi les sources de production d'électricité, ainsi qu'une diminution de la consommation d'électricité régionale, notamment grâce à des efforts intenses d'efficacité énergétique. Cette étude ciblée établit non seulement un cadre théorique pour comprendre la flexibilité des systèmes énergétiques dans le contexte de l'Occitanie, mais offre également des perspectives pratiques et des applications de ces méthodologies, guidant la région vers un avenir énergétique durable.

### B. Synthèse détaillée des principaux résultats de chaque chapitre

Cette thèse explore l'intégration des VRE dans la région d'Occitanie, en France, en se concentrant sur la flexibilité des systèmes électriques. Elle commence par un nouveau modèle de prévision combinant la décomposition de séries temporelles et des réseaux LSTM convolutifs, offrant des prédictions précises des besoins en flexibilité. Ensuite, elle introduit un modèle d'optimisation des coûts pour gérer l'offre et la demande de flexibilité, testé avec les données de l'Occitanie de 2021. La dernière partie utilise l'analyse de scénarios, projetant les besoins de flexibilité de la région jusqu'en 2050, et révélant des stratégies pour assurer la flexibilité du système électrique sous diverses hypothèses. Les résultats de chaque chapitre, bien que distincts dans leur focus, se lient ensemble pour former un récit complet qui illustre la nature multicouche de la flexibilité des systèmes électriques. La précision dans la prévision, telle que développée dans le premier chapitre, pose les bases pour le modèle d'optimisation du deuxième chapitre, qui à son tour est utilisé pour explorer les scénarios envisagés dans le troisième chapitre. Cette interconnexion signifie une intégration harmonieuse des méthodologies, où la sortie de l'une sert d'entrée pour l'autre, créant un effet en cascade de connaissances qui enrichit la compréhension globale des systèmes électriques régionaux.

i. Chapitre I : Prévisions des besoins de flexibilité du système électrique par méthode hybride d'apprentissage profond

Le premier chapitre de la thèse pose les bases fondamentales pour comprendre et quantifier les besoins en flexibilité des systèmes énergétiques, ce qui est essentiel pour développer et évaluer efficacement les stratégies d'optimisation et les analyses de scénarios dans les chapitres suivants. Il se penche sur la prévision des besoins en flexibilité des systèmes énergétiques nécessités par l'ascension des VRE. D'abord, ce chapitre présente au lecteur le concept de Charge Résiduelle (RL), utilisé pour approximer les besoins en flexibilité d'un système énergétique donné. En effet, la fonction RL incorpore à la fois la consommation d'électricité et la génération intermittente, et est donc un candidat idéal pour évaluer les besoins en termes de flexibilité positive (c'est-à-dire la production supplémentaire d'énergie nécessaire pour couvrir toute la demande) lorsque la fonction est positive, et de flexibilité négative (c'est-à-dire l'évacuation ou le stockage d'un surplus de production d'électricité) lorsque la fonction est négative. Ensuite, le chapitre éclaire le développement et l'application d'un modèle de prévision, conçu à partir d'une approche d'apprentissage profond hybride qui fusionne la précision analytique de la décomposition de séries temporelles (CEEMDAN) avec les capacités de prévision avancées des réseaux Long Short-Term Memory (LSTM) convolutifs.

La méthodologie déployée dans cette recherche est méticuleusement conçue pour améliorer la fiabilité des prévisions. Elle commence par une décomposition de séries temporelles pour extraire et analyser les modèles sous-jacents de la demande en électricité et

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de la production des VRE. Cette étape pose les bases pour l'application ultérieure des réseaux LSTM convolutifs, qui capturent et interprètent habilement les dépendances spatio-temporelles dans les données. Cette combinaison innovante permet au modèle de fournir des prévisions affinées qui sont essentielles pour la planification opérationnelle et la manœuvre stratégique des systèmes énergétiques qui incorporent des parts significatives de VRE.

Les principaux résultats de ce document sont doubles. D'un point de vue méthodologique, l'union des techniques de décomposition de séries temporelles et de modélisation de réseaux de neurones artificiels (ANN) aboutit à un modèle qui surpasse les méthodes de prévision traditionnelles en termes de consistance des prévisions dans le temps. Cela signifie que, comparé aux cadres de prévision traditionnels tels que les modèles Auto-Régressive Integrated Moving Average (ARIMA), les résultats de prévision donnés par notre approche restent précis période après période, sans avoir à recalibrer le modèle à chaque fois que de nouvelles données deviennent disponibles. En d'autres termes, une fois entièrement entraîné, notre modèle CEEMDAN-ConvLSTM-2D capture efficacement à la fois les dépendances à long et à court terme d'un phénomène séquentiel observé et peut donc prédire avec précision ses résultats futurs sur une base de séquence à séquence. D'un point de vue pratique, la précision du modèle proposé dans la prévision de la RL donne aux opérateurs de réseau et aux acteurs du marché l'aperçu prédictif nécessaire pour gérer efficacement la variabilité des VRE. En effet, la fonction RL encapsule à la fois la génération variable et la consommation d'électricité dans une variable unique qui est prédite avec précision sur une base horaire vingt-quatre heures à l'avance par notre modèle proposé. Cela ouvre la voie à des décisions plus éclairées concernant l'activation et l'allocation des ressources énergétiques, optimisant ainsi l'efficacité opérationnelle et aidant au développement stratégique des infrastructures énergétiques.



ii. Chapitre II : Un modèle régional de gestion de la flexibilité du système électrique et son application à la région Occitanie

Dans le second chapitre de la thèse, la recherche se concentre sur le cœur de la gestion de la flexibilité des systèmes électriques. Le chapitre introduit un modèle d'optimisation des coûts conçu pour naviguer dans les complexités de l'approvisionnement en flexibilité à partir d'un éventail de technologies. Le modèle se distingue non seulement par sa capacité à minimiser les coûts, mais aussi par son application à travers divers domaines technologiques, tels que les capacités de réponse instantanée du stockage par batteries et la fourniture d'énergie durable des centrales hydroélectriques.

Ce segment de la recherche souligne l'urgence de repenser la flexibilité des systèmes électriques à la lumière du déploiement rapide des capacités des VRE dans le mix électrique. Avec l'ascension des VRE et les problèmes d'intermittence qui en découlent, une approche réflexive de la gestion de la flexibilité des systèmes électrique devient indispensable pour soutenir le développement de ces sources de génération intermittentes.

Le chapitre propose un modèle d'optimisation des coûts qui relève ce défi. Le modèle est un assemblage méticuleux de sources régionales de flexibilité, répondant à la demande estimée de flexibilité à travers la fonction de RL. Il intègre un assortiment de technologies, y compris l'hydroélectricité, le stockage par batteries et la production thermique, chacune avec ses propres contraintes techniques de haut niveau. En faisant cela, il offre une vue régionale de l'approvisionnement en flexibilité qui peut être mobilisé pour correspondre à la variabilité induite par les VRE. Il est important de noter que notre objectif n'est pas d'évaluer

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l'autosuffisance potentielle de la région Occitanie en termes de gestion de la flexibilité, mais plutôt de fournir un aperçu du fonctionnement potentiel d'un système régional de gestion de la flexibilité des systèmes électriques pleinement intégré dans le réseau national. En effet, dans notre approche de modélisation, les échanges d'électricité entre les régions sont pris en compte dans les besoins de flexibilité, ce qui illustre la nature interconnectée des systèmes électriques régionaux qui sont intégrés dans les réseaux nationaux ou supranationaux.

L'application de ce modèle à la région française d'Occitanie, calibrée avec les données réelles pour l'année 2021 et résolue à une fréquence semi-horaire, révèle des résultats éclairants. Les résultats du modèle indiquent que les sources traditionnelles de flexibilité, principalement l'énergie nucléaire et l'hydroélectricité, seraient principalement utilisées pour répondre à la RL positive de l'Occitanie. Le classement de l'ordre de mérite utilisé dans le modèle a montré que ces technologies, en raison de leurs coûts marginaux inférieurs, sont les premiers choix pour répondre à la demande d'électricité. Fait intéressant, des technologies plus coûteuses comme les turbines alimentées au pétrole ou le stockage de batteries n'étaient pas nécessaires dans ce scénario. Les profils de charge des différentes sources de flexibilité affichent des modèles saisonniers distincts, avec une diminution de la production de moyens flexibles en été lorsque la génération PV atteint son pic, et une augmentation en hiver pour couvrir les charges de pointe.

Grâce à son application pratique, le modèle offre des aperçus inestimables pour les décideurs, en particulier dans le contexte de l'évolution des stratégies d'investissement pour les capacités flexibles, un domaine qui gagne en importance avec le développement croissant des ERV. Cela souligne le besoin critique d'une approche diversifiée dans la gestion de la flexibilité,

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s'adaptant à la nature dynamique de l'intégration des ERV. Un aspect crucial de l'analyse du modèle était l'évaluation des coûts pour fournir de la flexibilité au système énergétique de l'Occitanie. Cette enquête a révélé un modèle saisonnier prononcé dans les coûts, qui reflétait les fluctuations de la courbe de RL, étroitement liée au passage des saisons.

### iii. Chapitre III : LE futur de la flexibilité du système électrique en Occitanie : une analyse de scénarios

Le troisième chapitre déplace le focus de l'état actuel du système énergétique d'Occitanie vers ses futurs potentiels jusqu'en 2050, en utilisant une analyse de scénarios pour éclairer les différents chemins qu'il pourrait emprunter. Il ne s'agit pas d'une entreprise spéculative mais plutôt d'une approche méthodique pour comprendre les impacts des demandes énergétiques fluctuantes et de l'évolution du paysage de la production d'électricité. Le chapitre souligne l'importance de ces projections pour orienter la région vers un système électrique résilient capable de gérer les défis associés à de hautes pénétrations de VRE. En effet, nous développons trois scénarios qui envisagent trois directions potentielles pour le système électrique d'Occitanie. D'abord, nous proposons un scénario *Business-as-Usual* (BAU) où les tendances observées en termes de consommation d'électricité et de déploiement des VRE au cours de la dernière décennie sont simplement projetées jusqu'en 2050. Le second scénario incarne une approche volontaire car il est basé sur la proposition REPOS 2050 faite par la région Occitanie en 2017 [Région Occitanie, 2017]. Dans ce scénario, des efforts significatifs d'efficacité énergétique aboutissent à une réduction de la consommation globale d'électricité de 7 % par rapport au niveau de 2019. Parallèlement, de grandes parts d'énergies renouvelables telles que le solaire et l'éolien sont rapidement introduites dans le mix de

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production. Ces deux facteurs combinés révèlent un besoin significatif de flexibilité négative dans ce scénario. Enfin, le dernier scénario, nommé *Électrification Intensive*, vise à illustrer une trajectoire où le passage à l'électricité comme principal vecteur énergétique en 2050 entraîne une consommation plus élevée, couverte par le déploiement de près de 50 % du potentiel régional des ERV. Là encore, des quantités significatives de flexibilité négative sont requises, ainsi qu'une forte demande de flexibilité positive pendant les périodes hivernales.

La méthodologie appliquée dans cette analyse implique la création de trois scénarios alternatifs de la fonction de RL que le système énergétique d'Occitanie pourrait rencontrer d'ici 2050. Pour évaluer la répartition optimale des unités de production flexibles nécessaires pour maintenir l'équilibre du système, le modèle d'optimisation de l'ordre de mérite semi-horaire introduit au chapitre II est utilisé. Ce modèle est clé pour déterminer le déploiement stratégique de différentes sources d'énergie et technologies pour répondre à la demande projetée tout en assurant la fiabilité et l'efficacité économique du système électrique.

Les résultats présentés dans ce chapitre indiquent un besoin significatif d'investissement dans des capacités de production flexibles d'ici 2050, avec un accent sur l'hydroélectricité, le nucléaire et les solutions basées sur le marché comme essentiels pour intégrer les VRE dans le mix électrique d'Occitanie. Cependant, il est important de noter que dans nos simulations, les scénarios REPOS 2050 et *Électrification Intensive* se sont retrouvés avec des périodes non réalisables pendant environ 20 % de l'année. Cela signifie que le mix de flexibilité d'Occitanie tel qu'il est aujourd'hui ne peut pas satisfaire les exigences de flexibilité induites par ces scénarios pour un cinquième du temps. Ainsi, l'analyse met en évidence une forte dépendance anticipée sur le réseau national pour maintenir la sécurité de l'approvisionnement. En termes

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de coût moyen de flexibilité, le scénario REPOS 2050 semble être le plus coûteux. À l'opposé, et presque de manière surprenante, le scénario *Électrification Intensive* semble être le plus rentable en moyenne. En menant des analyses de sensibilité, l'étude explore également divers résultats qui peuvent influencer la flexibilité du système énergétique régional, offrant des aperçus précieux pour les décideurs politiques et les investisseurs dans la planification d'une infrastructure énergétique durable et adaptable. Ces analyses de sensibilité comprennent le test de diverses configurations pour le futur mix de flexibilité d'Occitanie, telles que les variantes d'*Interruption Nucléaire*, d'*Hydroélectricité Contrainte* ou de *Développement des Batteries*. Dans ces cas, les résultats du modèle indiquent de légers changements pour les courbes de génération des actifs flexibles et les coûts, ainsi qu'une augmentation de la faisabilité notamment dans le cas de la variante d'*Interruption Nucléaire*.

## C. Implications des résultats

Les implications de la recherche menée sont diversifiées. Pour les opérateurs de réseaux, le modèle de prévision amélioré offre une vision plus claire de la demande à venir et de la production variable, permettant une allocation plus efficace des ressources et réduisant ainsi les incidents de surproduction ou de sous-production coûteuses. Il sert également d'outil qui aide à façonner la transformation des infrastructures nécessaires pour accompagner le développement des VRE, car il fournit des perspectives sur les futures exigences de flexibilité. Pour les décideurs politiques, le modèle d'optimisation offre un cadre de prise de décision qui peut informer les choix opérationnels à court terme, ainsi que des idées sur les investissements nécessaires pour soutenir les objectifs à long terme induits par la transition vers des systèmes énergétiques décarbonés. Cela est particulièrement pertinent alors que les

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nations et les régions luttent avec les réalités logistiques de la transition vers les sources d'énergie renouvelables.

Pour l'industrie de l'énergie, ces découvertes offrent un aperçu des futurs possibles, facilitant des investissements plus éclairés qui peuvent stimuler la croissance de solutions énergétiques flexibles. En offrant un regard détaillé sur les scénarios futurs possibles pour la gestion de la flexibilité en Occitanie, la recherche facilite une compréhension plus profonde de l'évolution du paysage énergétique. Cette prévoyance permet au secteur de l'énergie d'investir stratégiquement dans des technologies et des infrastructures telles que l'hydroélectricité ou le réseau, qui sont alignées avec le besoin accru de flexibilité du système électrique. De tels investissements éclairés sont vitaux pour s'adapter et tirer parti de la prévalence croissante des VRE, garantissant que l'industrie reste résiliente et compétitive.

Pour la demande et la consommation d'énergie, les résultats de la thèse fournissent des aperçus intéressants. Le modèle de prévision amélioré prédit plus précisément la demande et la production de VRE, permettant un système d'approvisionnement en électricité plus réactif et efficace. Cette précision est cruciale à une époque où les modèles de consommation d'électricité deviennent de plus en plus dynamiques et complexes, influencés par des facteurs tels que la prolifération des appareils intelligents, l'évolution des comportements des consommateurs et le passage progressif à la mobilité électrique. Comprendre ces modèles aide à optimiser la distribution d'énergie, à minimiser les déchets et à garantir la fiabilité, ce qui est particulièrement important alors que les systèmes énergétiques évoluent pour intégrer davantage de sources d'énergie renouvelables intermittentes.

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Pour les ménages, les implications de la thèse sont également significatives. Des modèles de prévision et d'optimisation améliorés signifient que les consommateurs peuvent s'attendre à un approvisionnement en électricité plus stable. L'accent mis sur les systèmes électriques régionaux suggère également que les solutions peuvent être adaptées pour répondre plus efficacement aux besoins locaux, ce qui pourrait conduire à des services énergétiques plus personnalisés. De plus, la recherche soutient le développement d'infrastructures énergétiques durables, contribuant à l'objectif plus large de réduction des empreintes carbone et d'atténuation des impacts du changement climatique, ce qui profite aux ménages à la fois économiquement et environnementalement.

### D. Contributions à l'économie de l'énergie

La thèse enrichit le domaine académique de la recherche en économie de l'énergie, d'abord par le développement d'un modèle de prévision avancé utilisant des techniques d'apprentissage profond. Cette approche innovante améliore la précision des prédictions pour la demande en électricité et la génération des VRE, un aspect crucial pour une allocation efficace des ressources.

De plus, elle introduit le modèle *Optimiflex*, un cadre d'optimisation des coûts adapté à la gestion de la flexibilité des systèmes électriques. Ce modèle aide à naviguer dans les complexités associées à la recherche de flexibilité à partir de diverses technologies.

En outre, la recherche se penche sur l'analyse de scénarios, explorant les possibilités futures pour les systèmes électriques dans la région Occitanie jusqu'à l'année 2050. Cette

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approche prospective fournit des informations précieuses sur les impacts potentiels de niveaux variables d'intégration des VRE. Elle offre également une compréhension de la manière dont différents scénarios pourraient façonner la prise de décision stratégique dans le développement de l'infrastructure énergétique.

De plus, la thèse contribue à la compréhension des systèmes électriques régionaux, les positionnant comme un prisme pertinent et efficace pour analyser et modéliser les systèmes électriques. En effet, il est à noter que la littérature a encore peu exploré le sujet des systèmes électriques régionaux. Ce niveau d'abstraction pour représenter les systèmes électriques émerge ainsi comme une direction de recherche potentielle, car l'absence de représentation à ce niveau régional dans la littérature énergétique ne signifie pas que le sujet est sans pertinence, mais plutôt qu'il s'agit d'une nouvelle approche potentielle à favoriser pour l'inclusion des VRE dans les systèmes électriques. En se concentrant sur la région Occitanie, la recherche fournit une étude de cas détaillée de la manière dont les caractéristiques et spécificités régionales peuvent influencer l'intégration et la gestion des énergies renouvelables. Cette perspective régionale est particulièrement importante pour comprendre les nuances de la flexibilité des systèmes électriques, qui peuvent varier considérablement d'une région à l'autre en raison de différents mix de production, de modèles de consommation et de capacités d'infrastructure. L'approche régionale permet également des solutions plus adaptées et efficaces. Des solutions qui fonctionnent bien dans une région peuvent ne pas être aussi efficaces dans une autre en raison de ces facteurs variables. Cette perspicacité est cruciale pour les décideurs politiques et les fournisseurs d'énergie, car elle souligne la nécessité de stratégies personnalisées qui tiennent compte des réalités locales. Elle s'éloigne d'une approche universelle, plaidant pour des solutions énergétiques plus nuancées et spécifiques au contexte.



De plus, étudier les systèmes électriques à un niveau régional peut favoriser l'engagement et le soutien de la communauté. En alignant les stratégies énergétiques sur les caractéristiques et les besoins régionaux, les parties prenantes, y compris les gouvernements locaux et les communautés, peuvent être impliquées plus efficacement dans le processus décisionnel. Cela améliore non seulement l'acceptabilité et la pertinence des projets énergétiques, mais renforce également l'efficacité et la durabilité globales de la transition énergétique. Ainsi, cette thèse souligne l'importance de l'analyse régionale dans le contexte plus large de la recherche en économie de l'énergie, démontrant que les systèmes électriques régionaux présentent des opportunités et des défis uniques dans la transition vers les énergies renouvelables.

En résumé, cette thèse contribue non seulement au domaine académique de la recherche en économie de l'énergie à travers ses modèles de prévision et d'optimisation, mais aussi en soulignant l'importance des systèmes électriques régionaux. Elle fait progresser la compréhension de la manière dont ces systèmes peuvent être modélisés et gérés de manière efficace, offrant ainsi un cadre pour examiner la dynamique de la transition énergétique à l'échelle régionale.

## E. Remarques finales sur les résultats

En résumé, les résultats présentés dans cette thèse représentent un appel à l'action. Ils articulent une vision d'un avenir où les systèmes électriques ne sont pas seulement durables, mais également intrinsèquement flexibles et robustes. Ce travail réaffirme le rôle crucial de la flexibilité du système électrique dans la transition énergétique et souligne la nécessité d'une

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innovation et d'une planification stratégique continues. Les principaux enseignements de cette thèse soulignent l'importance de la prévoyance dans la conception et la gestion des systèmes énergétiques, et le rôle essentiel que jouent les modèles avancés de prévision et d'optimisation pour atteindre les objectifs doubles de sécurité énergétique et de durabilité environnementale. Alors que nous concluons cette exploration de la flexibilité du système électrique, nous sommes rappelés que le chemin vers un avenir décarboné est complexe, nécessitant une recherche assidue, une prévoyance stratégique et un engagement indéfectible envers l'innovation.

## 2. Limites de la thèse et perspectives de recherche

Dans la quête de rigueur et de précision académiques, il est crucial de reconnaître les contraintes et les limites inhérentes dans lesquelles cette recherche a été menée. La section suivante vise à discuter un peu plus des contraintes des méthodologies employées, de la spécificité des scénarios considérés et de l'applicabilité plus large des résultats. Bien que la recherche présentée ici apporte des contributions substantielles au domaine de la flexibilité des systèmes électriques, en particulier dans le contexte de la région Occitanie, elle s'accompagne de certaines mises en garde et exclusions qui doivent être prises en compte lors de l'interprétation des résultats. Ces limitations mettent non seulement en lumière les défis rencontrés pendant le processus de recherche, mais tracent également le champ pour de futures études pour construire sur les fondations établies par cette thèse.

## A. Prévvision

Dans le premier chapitre est présentée une approche innovante dans la prévision des besoins en flexibilité des systèmes électriques, utilisant principalement un modèle de type *Business-As-Usual* qui se base uniquement sur des données historiques. Cette méthodologie, bien qu'efficace pour fournir des prévisions horaires à la journée pour la fonction de RL, présente une limitation notable : sa capacité limitée à anticiper et à prendre en compte des événements sans précédent qui pourraient avoir un impact significatif sur la consommation et la production d'électricité. Des exemples de tels événements incluent des pandémies mondiales, des changements rapides dans la réglementation des marchés de l'électricité ou des percées technologiques inattendues qui pourraient modifier à la fois les coûts d'investissement et opérationnels. Cette limitation est particulièrement cruciale dans une ère où le paysage énergétique est de plus en plus sujet à des changements rapides et imprévisibles. Bien que le cadre CEEMDAN-ConvLSTM-2D soit utile pour la planification immédiate et les décisions opérationnelles, il peut ne pas équiper pleinement les opérateurs de systèmes électriques et les décideurs politiques des outils nécessaires pour naviguer dans la planification stratégique à long terme dans un secteur énergétique en constante évolution.

La limitation inhérente de cette approche de prévision ouvre une avenue significative pour la recherche future, en particulier dans le développement de méthodologies de prévision avancées. Les études futures dans ce domaine devraient viser à transcender les limitations de la dépendance aux données historiques, en intégrant des connaissances d'experts ainsi que des données en temps réel pour aborder l'ensemble des incertitudes et des complexités inhérentes aux systèmes électriques modernes. Cette approche permettra un modèle de prévision plus dynamique et réactif qui ne soit pas seulement basé sur les tendances passées, mais aussi

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adaptable aux conditions actuelles et aux perspectives d'experts, améliorant ainsi la précision et la fiabilité des prédictions, dans un mélange de science, de chocs anticipés et de connaissances institutionnelles. De plus, ces méthodologies de prévision avancées devraient être conçues pour s'adapter aux chocs ou aux événements de type 'cygne noir' – ces occurrences rares mais très impactantes qui perturbent les modèles établis et défient les prédictions conventionnelles. Le secteur de l'électricité, avec sa dépendance croissante aux sources renouvelables et l'évolution de la dynamique du marché, est particulièrement vulnérable à de tels événements. En développant des modèles de prévision qui peuvent prendre en compte ces variables, les chercheurs peuvent contribuer de manière significative à la robustesse et à la fiabilité des systèmes électriques.

### *B. Mécanismes d'effacement et plateformes Peer-to-Peer*

La recherche présentée dans la thèse aborde un aspect essentiel des systèmes électriques : l'effacement et les plateformes Peer-to-Peer (P2P) [Cortade et Poudou, 2021], mais elle révèle également une lacune significative dans ce domaine. L'absence d'une exploration détaillée des mécanismes d'effacement dans le cadre de la thèse souligne un domaine crucial pour de futures recherches et développements. Les mécanismes d'effacement sont de plus en plus reconnus comme une composante vitale des systèmes électriques contemporains, principalement en raison de leur potentiel à améliorer la flexibilité et l'efficacité du système. Leur intégration devient encore plus pertinente dans le contexte de l'intégration croissante des VRE, où l'équilibrage de l'offre et de la demande devient un défi complexe.

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Le concept d'effacement repose sur l'idée d'ajuster ou de déplacer l'utilisation de l'électricité en réponse aux conditions d'approvisionnement, telles que les périodes de forte demande ou lorsque la disponibilité des énergies renouvelables est élevée. Cette approche aide non seulement à stabiliser le réseau, mais joue également un rôle clé dans l'optimisation des modèles de consommation d'énergie, conduisant à des avantages économiques et environnementaux. Cependant, les modèles traditionnels d'effacement reposent souvent sur une communication à sens unique, où les consommateurs sont de simples récepteurs passifs d'ordres pour augmenter ou diminuer leur consommation d'énergie. C'est là que le rôle des plateformes P2P devient crucial.

Le commerce d'énergie P2P représente un changement de paradigme dans la distribution et la consommation d'énergie. Il permet aux consommateurs de devenir des participants actifs sur le marché de l'énergie, non seulement en tant qu'utilisateurs d'énergie, mais aussi en tant que producteurs (prosommateurs). Grâce aux plateformes P2P, les individus peuvent échanger directement l'énergie excédentaire générée à partir de sources renouvelables comme les panneaux solaires avec d'autres dans leur communauté ou région. Ce modèle démocratise non seulement la distribution d'énergie, mais incite également à l'adoption de sources d'énergie renouvelables en offrant un retour économique tangible sur l'investissement pour les producteurs d'énergie.

L'intégration des mécanismes d'effacement dans les plateformes P2P présente un axe de recherche passionnant. Une telle intégration pourrait conduire au développement de systèmes de commerce d'énergie en temps réel plus sophistiqués, équilibrant dynamiquement l'offre et la demande en fonction des modèles d'utilisation réels et des données de génération d'énergie

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renouvelable. Cette approche pourrait améliorer de manière significative la stabilité et l'efficacité du réseau, réduire les coûts énergétiques et promouvoir l'utilisation de sources renouvelables.

L'exploration des plateformes P2P dans le contexte des systèmes électriques régionaux représente un développement intéressant dans le domaine de la recherche énergétique. Les plateformes P2P, de par leur nature même, offrent une approche décentralisée du commerce et de la distribution d'énergie, les rendant particulièrement bien adaptées pour une application au sein des systèmes électriques régionaux.

Dans les systèmes électriques régionaux, le paysage énergétique est souvent défini par des sources d'énergie décentralisées, des modèles de consommation localisés et des capacités d'infrastructure spécifiques. Les plateformes P2P peuvent efficacement exploiter cette nature localisée, permettant aux ménages et aux entreprises d'une région de s'engager directement dans le processus de commerce d'énergie. Cet engagement direct facilite l'utilisation optimale des sources d'énergie renouvelable locales, telles que l'énergie solaire et éolienne, en permettant à l'énergie excédentaire générée par un utilisateur d'être vendue directement à un autre au sein de la même région. Cela améliore non seulement l'efficacité de la distribution d'énergie, mais encourage également l'adoption de sources d'énergie renouvelables en offrant une incitation financière tangible pour les consommateurs.

Le modèle décentralisé des plateformes P2P autonomise également les consommateurs, les transformant de récepteurs passifs d'énergie en participants actifs sur le marché de l'énergie. Ce changement favorise non seulement un plus grand sens de la communauté au sein des systèmes électriques régionaux, mais encourage également une approche plus

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responsable et engagée de la consommation et de la production d'énergie. Les consommateurs deviennent plus conscients de leurs modèles de consommation d'énergie et sont incités à ajuster leur consommation en fonction des signaux du marché en temps réel.

Cependant, le développement et la mise en œuvre de tels systèmes P2P régionaux viennent avec leur propre ensemble de défis. Ceux-ci incluent des obstacles technologiques liés au développement de plateformes robustes et sécurisées capables de gérer des données et des transactions en temps réel, des obstacles réglementaires et la nécessité de l'acceptation et de la participation des consommateurs. Aborder ces défis nécessite une approche multidisciplinaire, combinant des perspectives de domaines tels que l'informatique, l'économie, l'ingénierie et les sciences sociales.

En conclusion, bien que la thèse pose les bases pour comprendre la dynamique de la flexibilité des systèmes électriques, le développement potentiel de la flexibilité régionale par l'utilisation de plateformes P2P ouvre un champ de recherche riche et prometteur. Ce domaine ne détient pas seulement le potentiel de transformer la manière dont l'électricité est distribuée et consommée, mais s'aligne également avec les objectifs plus larges de création de systèmes électriques durables, efficaces et centrés sur l'utilisateur. Explorer ce domaine pourrait conduire à des avancées significatives dans la gestion de l'énergie et l'autonomisation des consommateurs.

## C. Explorer d'autres scénarios

L'exploration de scénarios alternatifs qui s'écartent des modèles *Business-As-Usual* présente une perspective de recherche convaincante, répondant à une limitation soulignée

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dans la thèse. Cette approche est particulièrement pertinente dans le secteur de l'énergie en rapide évolution, où les modèles traditionnels peuvent ne pas pleinement saisir les complexités et la dynamique des futurs systèmes énergétiques.

Dans le contexte de la thèse, l'accent a été principalement mis sur la prévision et l'optimisation de la flexibilité du système électrique dans certains cadres attendus basés sur les tendances historiques et les politiques existantes. Cependant, le paysage énergétique est soumis à une multitude d'influences, y compris des percées technologiques, des changements de politique, des changements sociétaux et des événements mondiaux inattendus, qui peuvent radicalement modifier la trajectoire des systèmes énergétiques.

Les recherches futures pourraient se plonger dans une gamme de scénarios alternatifs qui remettent en question les hypothèses conventionnelles. Ces scénarios pourraient englober des voies agressives de décarbonisation, l'adoption rapide de technologies émergentes, des changements significatifs dans le comportement des consommateurs ou la mise en œuvre de réformes politiques encore plus ambitieuses. Par exemple, les scénarios pourraient explorer les impacts d'une montée soudaine de l'adoption des véhicules électriques, une baisse rapide des coûts du Power-to-gas ou la mise en œuvre de politiques fiscales carbone strictes.

Une telle analyse de scénarios exploratoires fournirait des informations précieuses sur la résilience et l'adaptabilité des systèmes électriques dans diverses conditions. Elle aiderait également à identifier les risques et opportunités potentiels, guidant la planification stratégique et l'élaboration de politiques pour assurer des systèmes électriques robustes et durables. De plus, ces scénarios peuvent éclairer sur la nécessité de nouveaux investissements



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infrastructurels, de changements réglementaires et d'adaptations du marché nécessaires pour naviguer dans ces futurs alternatifs.

Cette perspective de recherche non seulement élargit la compréhension des futurs systèmes énergétiques potentiels, mais s'aligne également avec le besoin croissant d'approches innovantes et flexibles dans la planification et la gestion de l'énergie.

En résumé, cette thèse représente un pas vers un système électrique plus flexible, résilient et durable. Les perspectives et les avenues de recherche décrites ci-dessus mettent en évidence la nature multifacette du défi et l'approche interdisciplinaire requise pour y faire face. En explorant ces avenues, la recherche future peut s'appuyer sur les connaissances existantes, aborder les limitations et contribuer à la réalisation d'un système électrique adaptable et robuste qui peut répondre aux demandes du futur.





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## 1. Summary and findings

### A. Introduction to summary and findings

With the current energy transition comes a new paradigm for electricity generation. Increasing shares of Variable Renewable Energies (VRE) such as solar PV and wind power are included into power systems, and their decentralized nature invites to rethink the way power systems are designed and managed. Flexibility, or the ability of a given power system to rapidly and efficiently cope with changes either in demand or generation, becomes a critical issue that requires new approaches to be tackled. Indeed, the dual imperative to maintain energy security while advancing toward decarbonization places power system flexibility at the forefront of our collective efforts to forge sustainable energy systems. Thus, at the core of this dissertation lies a question that encapsulates the challenges and opportunities associated with the rise of VRE and their impact on flexibility management: How to manage at a the flexibility requirements induced but the rise of VRE ? This inquiry is particularly timely, unfolding in a global context where climate change imperatives, underscored by the Paris Agreement, compel us to reimagine our energy infrastructure.

This research carves out a novel trajectory by scrutinizing the burgeoning ascent of intermittent energy sources, such as solar and wind power, which are intrinsically

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decentralized. This shift underscores a fundamental need to reassess and reconfigure the traditionally centralized frameworks of national (or supranational) power systems. The argument developed here pivots on the rationale that a regional approach becomes increasingly pertinent and effective in addressing the challenges of power system flexibility. Unlike the centralized models, regional systems are better suited to integrate the decentralized nature of modern renewable energy sources, since they can unlock the potential of local flexibility sources more cost-efficiently and with a higher degree of accuracy. They offer a more tailored, responsive, and agile framework for managing the variability and uncertainty introduced by these intermittent energy sources. By focusing on regional power systems, this study aims to illuminate how regionalized management and decision-making can more effectively harness the potential of VRE, thereby enhancing overall system flexibility and reliability in an era marked by a significant shift towards sustainable energy solutions. Utilizing sophisticated forecasting techniques, developing an optimization model, and conducting thorough scenario analysis, this thesis provides an in-depth examination of how a regional power system can adeptly manage the variability of VRE.

Occitanie serves as an ideal case study for power system flexibility due to its significant integration of renewable energy sources, diverse energy mix, and unique regional energy policies, offering valuable insights into managing flexibility in a rapidly evolving renewable energy landscape. It is also much interesting because of its regional energy plan named REPOS 2050, which envisions a significant increase in VRE share amongst electricity generation sources, as well as a decrease in the regional electricity consumption, notably thanks to intense efforts of energy efficiency. This focused study not only establishes a theoretical framework for understanding power system flexibility in the context of Occitanie

but also offers practical insights and applications of these methodologies, guiding the region towards a sustainable energy future.

## B. Detailed synthesis of each chapter's findings

This thesis navigates the integration of VRE in the Occitanie region, France, focusing on power system flexibility. It starts with a novel forecasting model combining time-series decomposition and Convolutional LSTM networks, offering accurate predictions of flexibility requirements. Next, it introduces a cost-optimization model to manage the supply and demand of flexibility, tested with Occitanie 2021 data. The final part employs scenario analysis, projecting the region's power system flexibility until 2050, and revealing strategies for ensuring power system flexibility under various hypotheses. The findings from each chapter, while distinct in their focus, weave together to form a comprehensive narrative that illustrates the multi-layered nature of power system flexibility. The precision in forecasting, as developed in Chapter One, lays the groundwork for the optimization model of Chapter Two, which in turn is used to explore the scenarios envisioned in Chapter Three. This interconnectedness signifies a harmonious integration of methodologies, where the output of one serves as the input for another, creating a cascading effect of knowledge that enriches the overall understanding of regional power systems.

i. Chapter I: Forecasting power system flexibility requirements: A hybrid deep-learning approach

The first chapter of the thesis lays the foundational groundwork for understanding and quantifying the flexibility requirements of power systems, which is vital for effectively developing and assessing the subsequent optimization strategies and scenario analyses in the later chapters. It delves into the forecasting of power system flexibility requirements necessitated by the ascent of VREs. First, this chapter introduces the reader with the concept of Residual Load (RL), which is used to approximate the flexibility requirements of a given power system. Indeed, the RL function incorporates both electricity consumption and intermittent generation, and is therefore an ideal candidate for assessing the needs in terms of positive flexibility (i.e. required additional production of energy to cover all the demand) when the function is positive, and negative flexibility (i.e. required evacuation, or storage, of an electricity generation surplus) when the function is negative. Then, the chapter illuminates the development and application of a forecasting model, crafted from a hybrid deep-learning approach that fuses the analytical precision of time-series decomposition (CEEMDAN) with the advanced forecasting capabilities of Convolutional LSTM (Long Short-Term Memory) artificial neural networks.

The methodology deployed in this research is meticulously designed to enhance forecasting reliability. It begins with a time-series decomposition to extricate and analyze the underlying patterns in electricity demand and VRE generation. This step lays the groundwork for the subsequent application of Convolutional LSTM networks, which adeptly capture and interpret spatial-temporal dependencies in the data. This innovative combination enables the

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model to provide fine-tuned forecasts that are essential for the operational planning and strategic maneuvering of power systems that incorporate significant shares of VRE.

The main results of this paper are twofold. From a methodological point of view, the union of time-series decomposition and Artificial Neural Network (ANN) modeling techniques results in a model that outperforms traditional forecasting methods in terms of forecasting consistency over time. This means that compared to traditional forecasting frameworks such as Auto-Regressive Integrated Moving Average (ARIMA) models, the forecasting results given by our approach remain accurate period after period, without having to recalibrate the model each time new data becomes available. In other terms, once fully trained, our CEEMDAN-ConvLSTM-2D model efficiently captures both long- and short-term dependencies of an observed sequential phenomenon and can thus accurately predict its future outcomes on a sequence-to-sequence basis. From a practical point of view, the proposed model's accuracy in forecasting the Residual Load empowers grid operators and market actors with the predictive insight necessary to manage the variability of VRE effectively. Indeed, the RL function encapsulates both variable generation and electricity consumption in a unique variable that is accurately predicted on a hourly basis twenty-four hours in advance by our proposed model. This paves the way for more informed decisions regarding the activation and allocation of energy resources, thus optimizing operational efficiency and aiding in the strategic development of energy infrastructures.



ii. Chapter II: A regional power system flexibility management model and its application to French region Occitanie

In the second chapter of the thesis, the research moves towards the crux of power system flexibility management. The chapter introduces a cost-optimization model designed to navigate the complexities of sourcing flexibility from a spectrum of technologies. The model stands out not only for its ability to minimize costs but also for its application across diverse technological domains, such as the instantaneous response capabilities of battery storage and the enduring energy provision of pumped hydro storage.

This segment of the research emphasizes the urgent need to rethink power system flexibility in light of the rapid deployment of VRE capacities into the electricity mix. With the ascent of VRE and the consequent intermittency issues, a reflexive approach to managing power system flexibility becomes indispensable to support the development of these intermittent generation sources.

The chapter puts forward a cost-optimization model that confronts this challenge. The model is a meticulous assembly of regional sources of flexibility, meeting the estimated demand for flexibility through the Residual Load function. It incorporates an assortment of technologies, including hydropower, battery storage, and thermal generation, each with their respective high-level technical constraints. By doing so, it offers a regional view of the flexibility supply that can be mobilized to match the VRE-induced variability. It is important to note that our purpose is not to evaluate the potential self-sufficiency of Occitanie region in terms of flexibility management, but more to provide insight into the potential functioning of

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a regional power system flexibility management system that is fully incorporated in the national grid. Indeed, in our modeling approach, electricity exchanges between regions are taken into account in the flexibility requirements, which illustrates the interconnected nature of regional power systems that are embedded in national or supranational grids.

The application of this model to the French region of Occitanie, calibrated with the actual data for the year 2021 and resolved at a half-hourly frequency, reveals insightful results. The model's results indicated that traditional flexibility sources, mainly nuclear power and hydropower, would primarily be used to meet Occitanie RL when it is positive. The merit-order ranking employed in the model showed that these technologies, due to their lower marginal costs, are the first choices for serving the electricity demand. Interestingly, more expensive technologies like oil-fired turbines or battery storage were not required in this scenario. The load profiles of different flexibility sources displayed distinct seasonal patterns, with a decrease in flexible means production during summer when PV generation peaked, and an increase in winter to cover peak loads.

Through its practical application, the model offers invaluable insights for decision-makers, especially in the context of evolving investment strategies for flexible capacities, an area gaining importance with the increasing development of VRE. This highlights the critical need for a diversified approach in flexibility management, adapting to the dynamic nature of VRE integration. A pivotal aspect of the model's analysis was the cost evaluation for providing flexibility to the Occitanie power system. This investigation unveiled a pronounced seasonal pattern in costs, which mirrored the fluctuations in the Residual Load curve, closely tied to the intermittent nature of VRE like solar and wind power. Importantly, the median

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marginal price was in line with the operational costs of nuclear technology, which remained a consistent contributor to the system's flexibility due to its minimum operating capacity constraint of 20%. The total cost of ensuring system flexibility in this scenario amounted to approximately 1.335 billion euros over the year, aligning with the national expenditures on flexibility management by RTE in 2021. This alignment underscores the model's effectiveness in capturing the economic realities of flexibility management in a power system increasingly influenced by VRE development.

### iii. Chapter III: The future of power system flexibility in Occitanie: A scenario analysis

Chapter three shifts the focus from the current state of the Occitanie power system to its potential futures up to the year 2050, utilizing scenario analysis to illuminate the various paths it might take. This isn't a speculative endeavor but rather a methodical approach to understanding the impacts of fluctuating energy demands and the evolving landscape of energy production. The chapter underscores the importance of these projections for steering the region towards a resilient power system that can handle the challenges associated with high penetrations of VRE. Indeed, we develop three scenarios that undertake three potential directions for the Occitanie energy system. First, we propose a *Business-as-Usual* (BAU) scenario in which the observed tendencies in terms of electricity consumption and VRE deployment over the past decade are simply projected up to 2050. The second scenario embodies a voluntary approach as it is based on the REPOS 2050 proposal made by region Occitanie in 2017. In this scenario, significant efforts of energy efficiency end up in a reduction of the overall electricity consumption by 7% compared to the 2019 level.

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Meanwhile, large shares of renewable energies such as solar and wind power are rapidly introduced into the generation mix. These two factors combined reveal a significant need for negative flexibility in this scenario. Finally, the last scenario, named *Intensive Electrification*, aims to illustrate a trajectory in which the shift towards electricity as the main energy vector in 2050 results in a higher consumption, which is covered by deploying almost 50% of the region's potential for VRE. Here again, significant amounts of negative flexibility are required, as well as high positive flexibility demand during winter times.

The methodology applied in this analysis involves the creation of three alternate Residual Load function scenarios that the Occitanie power system could encounter by 2050. To assess the optimal dispatch of flexible power units necessary to maintain system balance, the half-hourly merit-order optimization model introduced in chapter 2 is used. This model is key to determining the strategic deployment of different energy sources and technologies to meet the projected demand while ensuring the reliability and economic efficiency of the power system.

The findings presented in this chapter indicate a significant requirement for investment in flexible generation capacities by 2050, with a spotlight on hydropower, nuclear, and market-based solutions as pivotal to integrating VRE into Occitanie power mix. However, it is important to note that in our simulations, the REPOS 2050 and *Intensive Electrification* scenarios ended up having infeasible periods for around 20% of the year. This means that the Occitanie flexibility mix as it is today cannot serve the flexibility requirements induced by these scenarios for one fifth of the time. Thus, the analysis highlights an anticipated strong dependence on the national grid for maintaining supply security. In terms of average

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flexibility cost, the REPOS 2050 scenario seems to be the most expensive. Oppositely, and almost surprisingly, the *Intensive Electrification* scenario appears to be the most cost effective on average. By conducting sensitivity analyses, the study also explores various outcomes that may influence the regional power system's flexibility, offering valuable insights for policymakers and investors in planning for a sustainable and adaptable energy infrastructure. These sensitivity analyses include the testing of various configurations for the future Occitanie flexibility mix, such as *Nuclear interruption*, *Constrained Hydropower* or *Battery development* variants. In these cases, the model results indicate slight changes for the generation curves of flexible assets and costs, as well as an increase in feasibility notably in the case of the *Nuclear interruption* variant.

### C. Implications of findings

The implications of the research conducted are many faceted. For grid operators, the enhanced forecasting model provides a clearer picture of upcoming demand and variable generation, allowing for more efficient allocation of resources and thus reducing the incidence of costly overproduction or underproduction. It also serves as a tool that helps to shape the transformation of infrastructures needed to accompany the development of VRE, as it provides insights on future flexibility requirements. For policymakers, the optimization model offers a decision-making framework that can inform short-term operational choices, as well as insights into the needed investments to support the long-term goals induced by the transition towards decarbonized power systems. This is particularly relevant as nations and regions grapple with the logistical realities of transitioning to renewable energy sources.

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For the energy industry, these findings offer a glimpse into the possible futures, facilitating more informed investment that can stimulate the growth of flexible energy solutions. By offering a detailed look into potential future scenarios for the Occitanie flexibility management, the research facilitates a deeper understanding of the evolving energy landscape. This foresight enables the energy sector to strategically invest in technologies and infrastructures such as hydropower or grid, that are aligned with the increased need for power system flexibility. Such informed investments are vital for adapting to and capitalizing on the increasing prevalence of VREs, ensuring that the industry remains resilient and competitive.

For energy demand and consumption, the thesis' findings provide interesting insights. The enhanced forecasting model predicts demand and VRE generation more accurately, enabling a more responsive and efficient electricity supply system. This precision is crucial in an era where electricity consumption patterns are becoming increasingly dynamic and complex, influenced by factors such as the proliferation of smart devices, changing consumer behaviors, and the gradual shift to electric mobility. Understanding these patterns helps in optimizing energy distribution, minimizing waste, and ensuring reliability, which is particularly important as energy systems transition to incorporate more intermittent renewable energy sources.

For households, the implications of the thesis are also meaningful. Improved forecasting and optimization models mean that consumers can expect more stable electricity supply. The focus on regional power systems also suggests that energy solutions can be tailored to meet local needs more effectively, potentially leading to more personalized energy services. Moreover, the research supports the development of sustainable energy

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infrastructures, contributing to the broader goal of reducing carbon footprints and mitigating climate change impacts, which benefits households both economically and environmentally.

### D. Contributions to the field

The thesis enriches the academic field of energy research, firstly through the development of an advanced forecasting model employing deep learning techniques. This innovative approach enhances the accuracy of predictions for electricity demand and the VRE generation, a crucial aspect for efficient resource allocation.

Additionally, it introduces the *Optimiflex* model, a cost-optimization framework tailored for power system flexibility management. This model aids in navigating the complexities associated with sourcing flexibility from diverse technologies.

Moreover, the research delves into scenario analysis, exploring future possibilities for power systems in the Occitanie region up to the year 2050. This forward-looking approach provides valuable insights into the potential impacts of varying levels of VRE integration. Furthermore, it offers an understanding of how different scenarios might shape strategic decision-making in energy infrastructure development.

Additionally, the thesis makes a contribution to the understanding of regional power systems, positioning them as a relevant and effective lens for analyzing and modeling power systems. Indeed, it is noticeable that the literature still has little explored the topic of regional

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power systems. This level of abstraction for representing power systems thus emerges as a potential new research direction, since the absence of such regional level representation in the energy literature does not mean that the topic is irrelevant, but more that it is a potential new approach to favor the inclusion of VRE within power systems. By focusing on the Occitanie region, the research provides a detailed case study of how regional characteristics and specificities can influence the integration and management of renewable energies. This regional perspective is particularly important in understanding the nuances of power system flexibility, which can vary significantly from one area to another due to different generation mixes, consumption patterns, and infrastructural capabilities. The regional approach also allows for more tailored and effective solutions. Solutions that work well in one region might not be as effective in another due to these varying factors. This insight is crucial for policymakers and energy providers as it emphasizes the need for customized strategies that consider local realities. It moves away from a one-size-fits-all approach, advocating for more nuanced and context-specific energy solutions.

Moreover, studying power systems at a regional level can foster community engagement and support. By aligning energy strategies with regional characteristics and needs, stakeholders, including local governments and communities, can be more effectively involved in the decision-making process. This not only improves the acceptability and suitability of energy projects but also enhances the overall efficiency and sustainability of the energy transition. Thus, this thesis underscores the importance of regional analysis in the broader context of energy research, demonstrating that regional power systems present unique opportunities and challenges in the transition to renewable energies.



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In summary, this thesis not only contributes to the academic field of energy research through its forecasting and optimization models but also by highlighting the significance of regional power systems. It advances the understanding of how these systems can be effectively modeled and managed, thereby offering a framework for examining the dynamics of energy transition at a regional scale.

### E. Closing remarks on findings

In summation, the findings presented in this thesis represent a call to action. They articulate a vision of a future where power systems are not only sustainable but also inherently flexible and robust. This work reaffirms the critical role of power system flexibility in the energy transition and highlights the need for continued innovation and strategic planning. The key takeaways from this thesis underscore the importance of foresight in energy system design and management, and the pivotal role that advanced forecasting and optimization models play in achieving the dual goals of energy security and environmental sustainability. As we conclude this exploration of power system flexibility, we are reminded that the journey towards a decarbonized future is one of complexity, requiring diligent research, strategic foresight, and an unwavering commitment to innovation.

## 2. Limitations of the thesis and research perspectives

In the pursuit of academic rigor and precision, it is crucial to acknowledge the inherent constraints and boundaries within which this research has been conducted. The following section aims to discuss a bit more the constraints of the methodologies employed, the specificity of the scenarios considered, and the broader applicability of the findings. While the research herein provides substantial contributions to the field of power system flexibility, especially within the context of the Occitanie region, it is accompanied by certain caveats and exclusions that must be taken into account when interpreting the results. These limitations not only highlight the challenges faced during the research process but also outline the scope for future studies to build upon the foundations laid by this thesis.

### A. Forecasting

In the first chapter is presented an innovative approach in forecasting power system flexibility requirements, predominantly employing a "Business-As-Usual" model that relies uniquely on historical data. This methodology, while effective in providing day-ahead hourly forecasts for the Residual Load function, exhibits a notable limitation: its constrained ability to anticipate and account for unprecedented events that could significantly impact electricity consumption and generation. Examples of such events include global pandemics, rapid changes in electricity market regulations, or unexpected technological breakthroughs that might alter both capital and operational costs. This limitation is particularly crucial in an era where the energy landscape is increasingly subject to rapid and unpredictable changes. While the CEEMDAN-ConvLSTM-2D framework is useful for immediate planning and operational

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decisions, it may not fully equip power system operators and policymakers with the tools needed to navigate long-term strategic planning in an ever-evolving energy sector.

The inherent limitation of this forecasting approach opens up a significant avenue for future research, particularly in the development of advanced forecasting methodologies. Future studies in this realm should aim to transcend the limitations of historical data reliance, incorporating expert knowledge as well as real-time data to address the full spectrum of uncertainties and complexities inherent to modern power systems. This approach will enable a more dynamic and responsive forecasting model that is not only grounded in past trends but also adaptable to current conditions and expert insights, thereby enhancing the accuracy and reliability of predictions, in a mix of science, shocks and institutional knowledge. Moreover, these advanced forecasting methodologies should be designed to adapt to shocks or 'black swan' events – those scarce but highly impactful occurrences that disrupt established patterns and defy conventional predictions. The electricity sector, with its increasing reliance on renewable sources and evolving market dynamics, is particularly vulnerable to such events. By developing forecasting models that can account for these variables, researchers can significantly contribute to the robustness and reliability of energy systems.

## B. Demand-response mechanisms and *Peer-to-Peer* platforms

The research presented in the thesis touches upon an essential aspect of power systems – demand response and Peer-to-Peer (P2P) platforms [Cortade and Poudou, 2021] – but it also reveals a significant gap in this area. The absence of a detailed exploration of demand-response mechanisms within the thesis's scope highlights a crucial area for further research

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and development. Demand-response mechanisms are increasingly recognized as a vital component of contemporary power systems, primarily due to their potential to enhance system flexibility and efficiency. Integrating these mechanisms becomes even more pertinent in the context of the growing integration of VRE, where balancing supply and demand becomes a complex challenge.

The concept of demand response revolves around the idea of adjusting or shifting electricity usage in response to supply conditions, such as peak demand periods or when renewable energy availability is high. This approach not only helps in stabilizing the grid but also plays a key role in optimizing energy consumption patterns, leading to economic and environmental benefits. However, traditional demand-response models often rely on one-way communication, where consumers are mere passive recipients of commands to increase or decrease their energy usage. This is where the role of P2P platforms becomes pivotal.

P2P energy trading represents a paradigm shift in how energy is distributed and consumed. It allows consumers to become active participants in the energy market, not just as energy users but also as producers (prosumers). Through P2P platforms, individuals can trade excess energy generated from renewable sources like solar panels directly with others in their community or region. This model not only democratizes energy distribution but also incentivizes the adoption of renewable energy sources by providing a tangible economic return on investment for energy producers.

The integration of demand-response mechanisms into P2P platforms presents an exciting research avenue. Such integration could lead to the development of more sophisticated, real-

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time energy trading systems that dynamically balance supply and demand based on actual usage patterns and renewable energy generation data. This approach could significantly enhance grid stability and efficiency, reduce energy costs, and promote the use of renewable sources.

The exploration of Peer-to-Peer (P2P) platforms within the context of regional power systems represents an interesting development in the field of energy research. P2P platforms, by their very nature, offer a decentralized approach to energy trading and distribution, making them particularly well-suited for application within regional power systems.

In regional power systems, the energy landscape is often defined by decentralized energy sources, localized consumption patterns, and infrastructural capabilities. P2P platforms can effectively tap into this localized nature, enabling households and businesses within a region to engage directly in the energy trading process. This direct engagement facilitates the optimal utilization of local renewable energy sources, such as solar and wind power, by allowing excess energy generated by one user to be sold directly to another within the same region. This not only enhances the efficiency of energy distribution but also encourages the adoption of renewable energy sources by providing a tangible financial incentive for consumers.

The decentralized model of P2P platforms also empowers consumers, transforming them from passive recipients of energy to active participants in the energy market. This shift not only fosters a greater sense of community within regional power systems but also encourages a more responsible and engaged approach to energy consumption and production. Consumers

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become more aware of their energy usage patterns and are incentivized to adjust their consumption based on real-time market signals.

However, the development and implementation of such regional P2P systems come with its own set of challenges. These include technological barriers related to the development of robust and secure platforms capable of handling real-time data and transactions, regulatory hurdles, and the need for consumer acceptance and participation. Addressing these challenges requires a multi-disciplinary approach, combining insights from fields such as computer science, economics, engineering, and social sciences.

In conclusion, while the thesis lays the groundwork in understanding the dynamics of power system flexibility, the potential development of regional flexibility through the use of P2P platforms opens up a rich and promising field for future research. This area not only holds the potential to transform the way energy is distributed and consumed but also aligns with the broader goals of creating sustainable, efficient, and user-centric energy systems. Exploring this domain could lead to significant advancements in energy management and empowering consumers.

### C. Exploration of diverse scenarios

Exploring alternative scenarios that deviate from the "Business-As-Usual" models presents a compelling research perspective, addressing a limitation highlighted in the thesis.

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This approach is particularly relevant in the rapidly evolving energy sector, where traditional models may not fully capture the complexities and dynamics of future energy systems.

In the context of the thesis, the focus has primarily been on forecasting and optimizing power system flexibility within certain expected frameworks based on historical trends and existing policies. However, the energy landscape is subject to a multitude of influences, including technological breakthroughs, policy shifts, societal changes, and unexpected global events, which can drastically alter the trajectory of energy systems.

Future research could delve into a range of alternative scenarios that challenge conventional assumptions. These scenarios could encompass aggressive decarbonization pathways, the rapid adoption of emerging technologies, significant changes in consumer behavior, or the implementation of revolutionary policy reforms. For instance, scenarios could explore the impacts of a sudden surge in electric vehicle adoption, a rapid decline in Power-to-gas costs, or the implementation of stringent carbon taxation policies.

Such exploratory scenario analysis would provide valuable insights into the resilience and adaptability of power systems under various conditions. It would also help in identifying potential risks and opportunities, guiding strategic planning and policymaking to ensure robust and sustainable power systems. Additionally, these scenarios can shed light on the need for new infrastructural investments, regulatory changes, and market adaptations required to navigate these alternative futures.

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This research perspective not only broadens the understanding of potential future energy systems but also aligns with the increasing need for innovative and flexible approaches in energy planning and management.

In a nutshell, this thesis represents a step toward a more flexible, resilient, and sustainable power system. The perspectives and research avenues outlined above highlight the multifaceted nature of the challenge and the interdisciplinary approach required to address it. By exploring these avenues, future research can build upon the existing knowledge, address the limitations, and contribute to the realization of an adaptable and robust power system that can meet the demands of the future.





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# APPENDICES

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## APPENDIX 1

### A. Long Short-Term Memory (LSTM)

LSTM working principles and equations are formulated here following the descriptions made in [Coronati et al., 2021 ; Graves, 2014].

In a LSTM network, the input layer contains a number of neurons equal to the size of the dataset. In the hidden layers, neurons are organized to form a *memory cell*, i.e. a direct sequential graph of neurons able to keep track of temporal dependencies within a dataset . At the end of the network, the output layer comprises a number of neurons equal to the expected output length.

Each time new information passes through the LSTM layers, a *forget gate* determine if the memory cell state  $C_t$  should be updated or not. To achieve this, the forget gate activation values  $f_t$  are computed by taking as inputs the current values of both data and weights connecting it to the input layer -respectively  $x_t$  and  $W_{f,x}$ - but also the previous outputs of the LSTM layer  $h_{t-1}$  and  $W_{f,h}$ , the previous cell state outputs  $C_{t-1}$  and  $W_{f,c}$  and the weights of the forget gate term bias term  $b_f$ , and applying to them a sigmoid function  $\sigma$ . This way, the output of the forget gate is a value between 0 (completely remove information for the cell state) to 1 (keep full information).

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$$(1) \quad f_t = \sigma(W_{f,x}x_t + W_{f,h}h_{t-1} + W_{f,c} \circ C_{t-1} + b_f)$$

Where  $\circ$  denotes the Hadamard product. Once the forget gate has determined which incoming information has to be discarded from the cell state, the *input gate* evaluates if some new information has to be stored in the cell. Here again, the input gate activation values  $i_t$  are calculated by using a sigmoid function on current inputs and bias and previous outputs.

$$(2) \quad i_t = \sigma(W_{i,x}x + W_{i,h}h_{t-1} + W_{i,c} \circ C_{t-1} + b_i)$$

While the input gate determines which information needs to be stored in the cell state, candidate values for the cell state  $\tilde{C}_t$  are generated using a hyperbolic tangent function on current inputs and bias and past hidden states.

$$(3) \quad \tilde{C}_t = \tanh(W_{c,x}x_t + W_{c,h} \circ h_{t-1} + b_i)$$

Merging these previous steps altogether provokes the updating of the current cell state  $C_t$ , using  $f_t \circ C_{t-1}$  to discard incoming information and  $i_t \circ \tilde{C}_t$  to store useful information.

$$(4) \quad C_t = f_t \circ C_{t-1} + i_t \circ \tilde{C}_t$$

Finally, an *output gate* selects information in the cell state that will be useful to perform the forecasting task by applying a sigmoid function to current inputs bias and cell state and previous hidden states.

$$(5) \quad o_t = \sigma(W_{o,x}x_t + W_{o,h}h_{t-1} + W_{o,c} \circ C_t + b_o)$$

To make sure the current hidden states values stay between -1 and 1, a hyperbolic tangent function of the current cell state is multiplied by the output sigmoid function  $o_t$ .

$$(6) \quad h_t = o_t \circ \tanh(C_t)$$

## B. Convolutional Long Short-Term Memory (ConvLSTM)

In a ConvLSTM network, inputs  $x$ , cell states  $C$ , hidden states  $h$  and gates  $i$ ,  $f$  and  $o$  are 3D tensors and products between weights and values of current inputs and past hidden states are replaced by a convolution operators  $*$  [Shi et al., 2015].

$$(1) \quad f_t = \sigma(W_{f,x} * x_t + W_{f,h} * h_{t-1} + W_{f,c} \circ C_{t-1} + b_f)$$

$$(2) \quad i_t = \sigma(W_{i,x} * x + W_{i,h} * h_{t-1} + W_{i,c} \circ C_{t-1} + b_i)$$

$$(3) \quad \tilde{C}_t = \tanh(W_{c,x} * x_t + W_{c,h} * h_{t-1} + b_i)$$

$$(4) \quad C_t = f_t \circ C_{t-1} + i_t \circ \tilde{C}_t$$

$$(5) \quad o_t = \sigma(W_{o,x} * x_t + W_{o,h} * h_{t-1} + W_{o,c} \circ C_t + b_o)$$

$$(6) \quad h_t = o_t \circ \tanh(C_t)$$



## APPENDIX 2

## A. Scenarios comparison

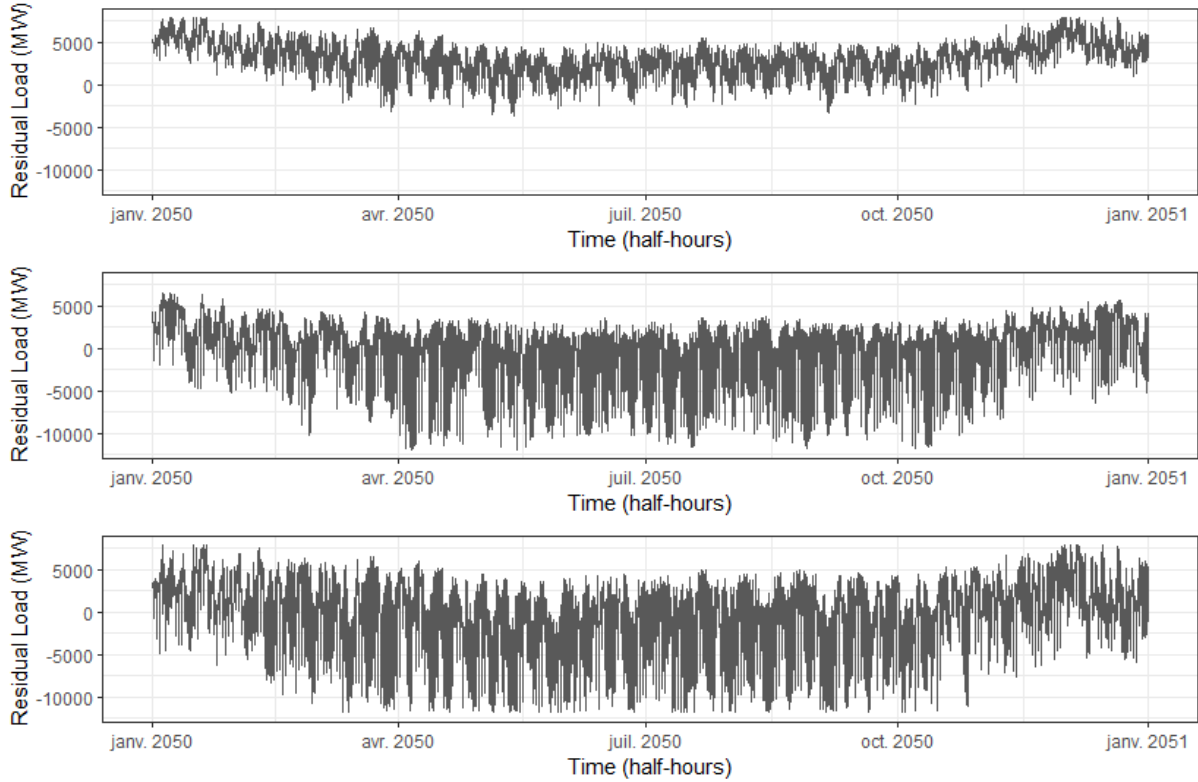


Figure 29 : . Half-hourly RL curves for the year 2050 in the *Business-as-Usual* scenario (up), the REPOS scenario (middle), and the *Intensive Electrification* scenario (down)

Scenario	Increase in electricity consumption	PV capacity by 2050 (MW)	Onshore wind capacity by 2050 (MW)	Offshore wind capacity by 2050 (MW)
<i>Business-as-Usual</i>	+22%	6 810	4 750	0
REPOS 2050	-7%	15 070	5 500	3 000
<i>Intensive Electrification</i>	+39%	20 000	10 000	5 000

Table 14 : Summary of the main hypothesis used to build the three scenarios



## B. Infeasible periods

	Baseline	Nuclear interruption	Constraint Hydropower	Battery Development	Fossil Fuels Exclusion
<i>Business-as-Usual</i>	0%	0.0002%	0%	0%	0%
REPOS 2050 <i>Intensive</i>	19.5%	17.4%	21.6%	19.5%	19.5%
<i>Electrification</i>	21.8%	19.8%	21.8%	21.7%	21.8%

Table 15 : Percentage of time (over 17 520 half-hours for the 2050 year) in which the model ends up with infeasible solution for the optimal dispatch of flexibility problem, according to scenarios and parametrizations

C. Nuclear interruption results

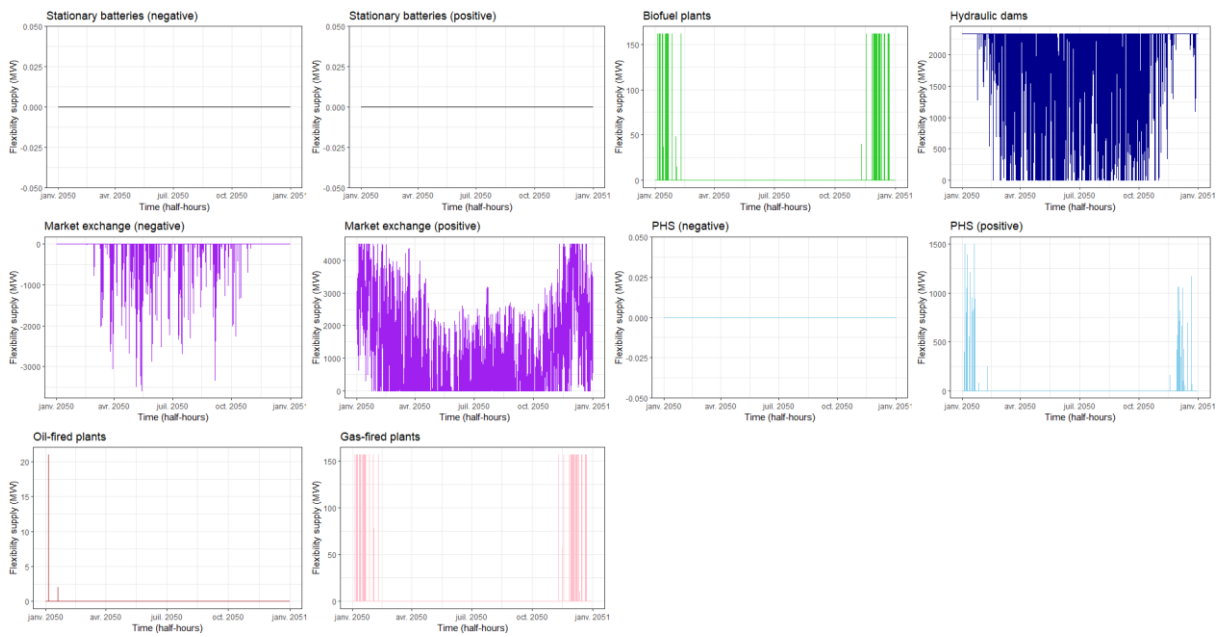


Figure 30 : Half-hourly production curves of flexible technologies in the *Business-as-Usual* scenario with *Nuclear Interruption* parametrization

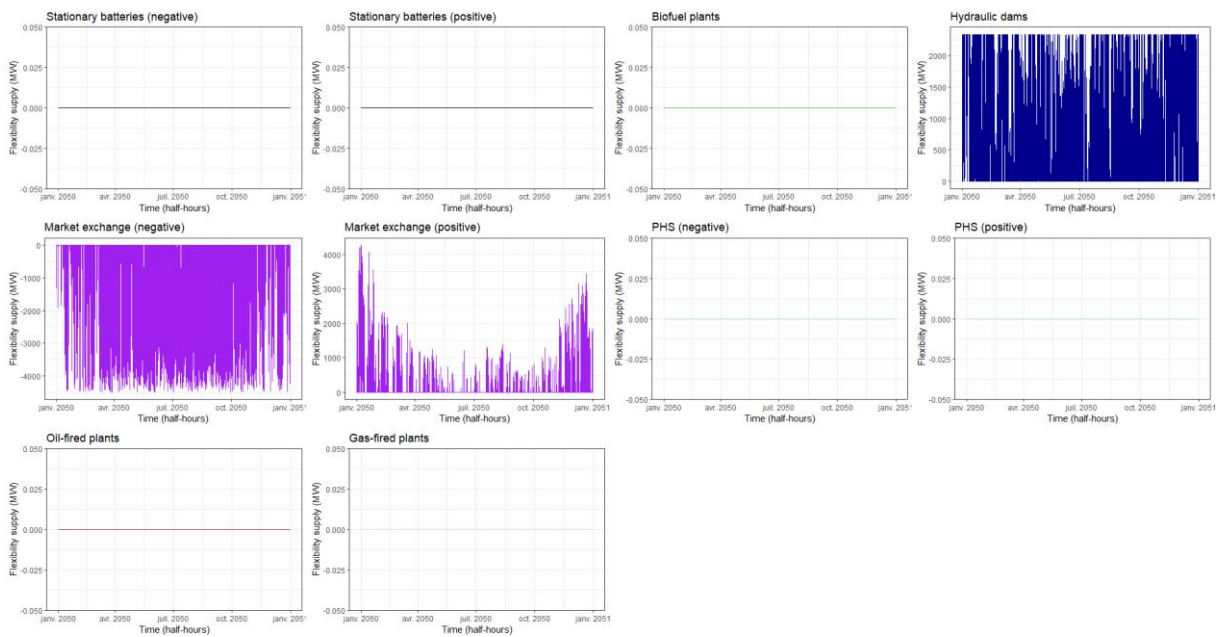


Figure 31 : Half-hourly production curves of flexible technologies in the REPOS 2050 scenario with *Nuclear Interruption* parametrization

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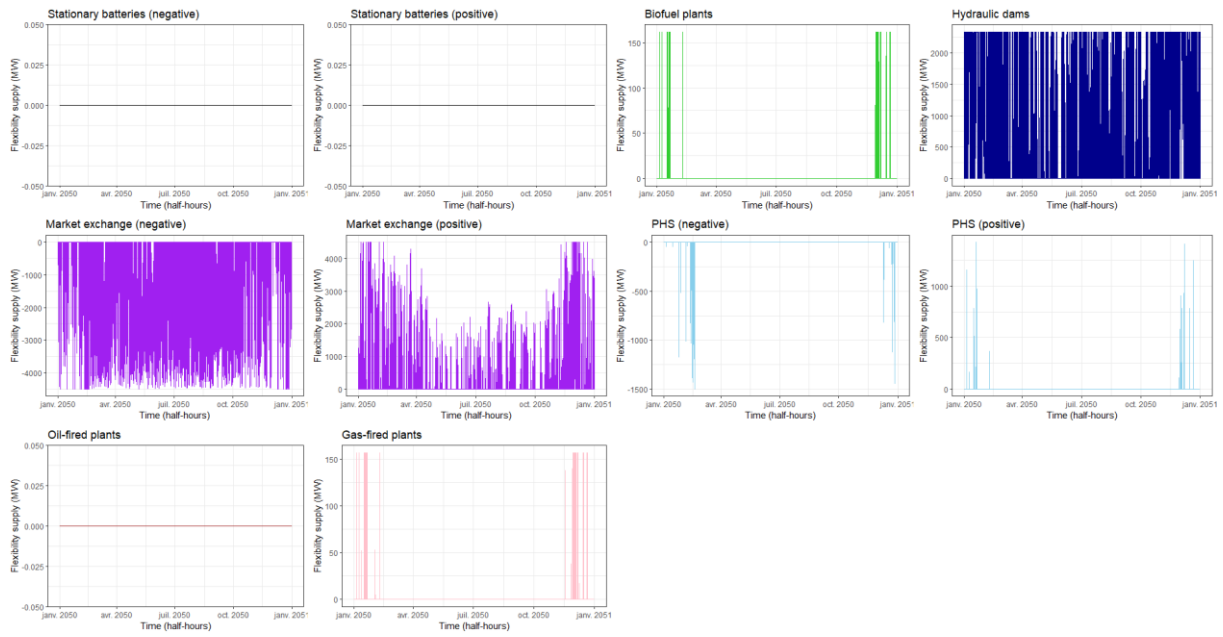


Figure 32 : Half-hourly production curves of flexible technologies in the *Intensive Electrification* scenario with *Nuclear Interruption* parametrization

D. Constrained hydropower results

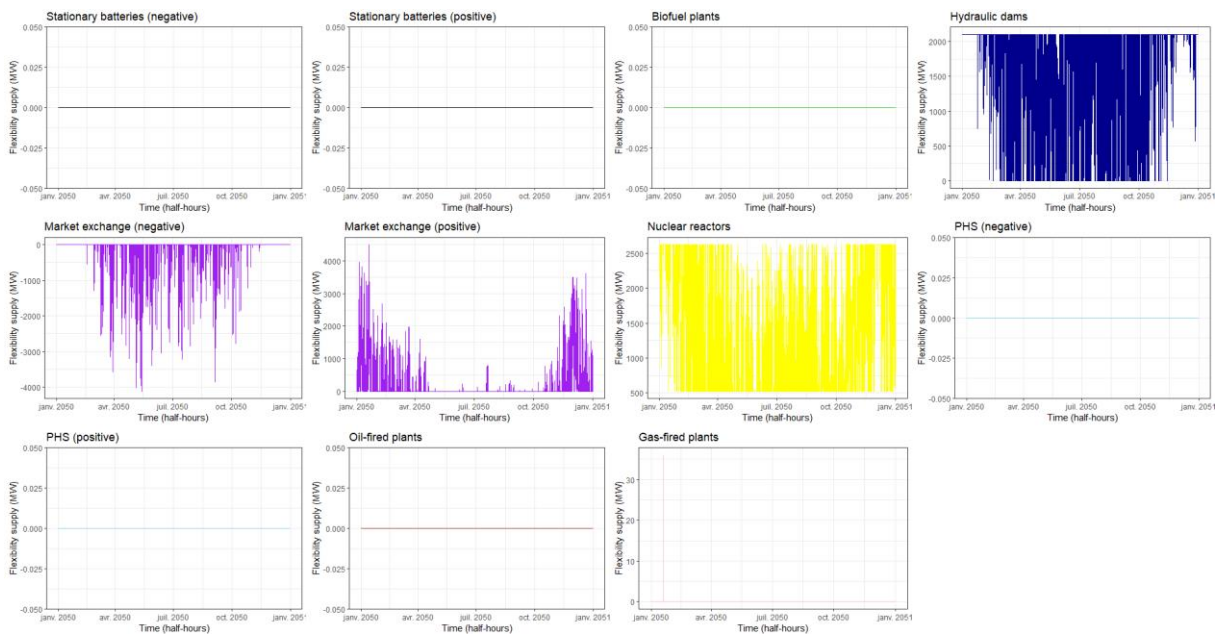


Figure 33 : Half-hourly production curves of flexible technologies in the *Business-as-Usual* scenario with *Constrained hydropower* parametrization

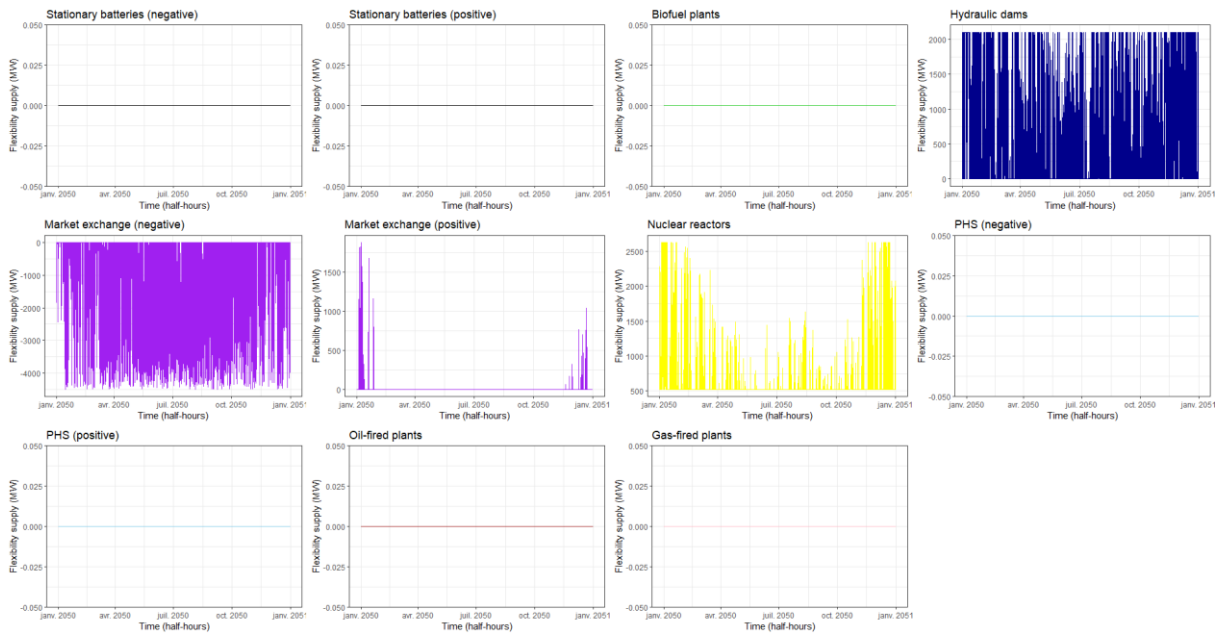


Figure 34 : Half-hourly production curves of flexible technologies in the REPOS scenario with *Constrained hydropower* parametrization

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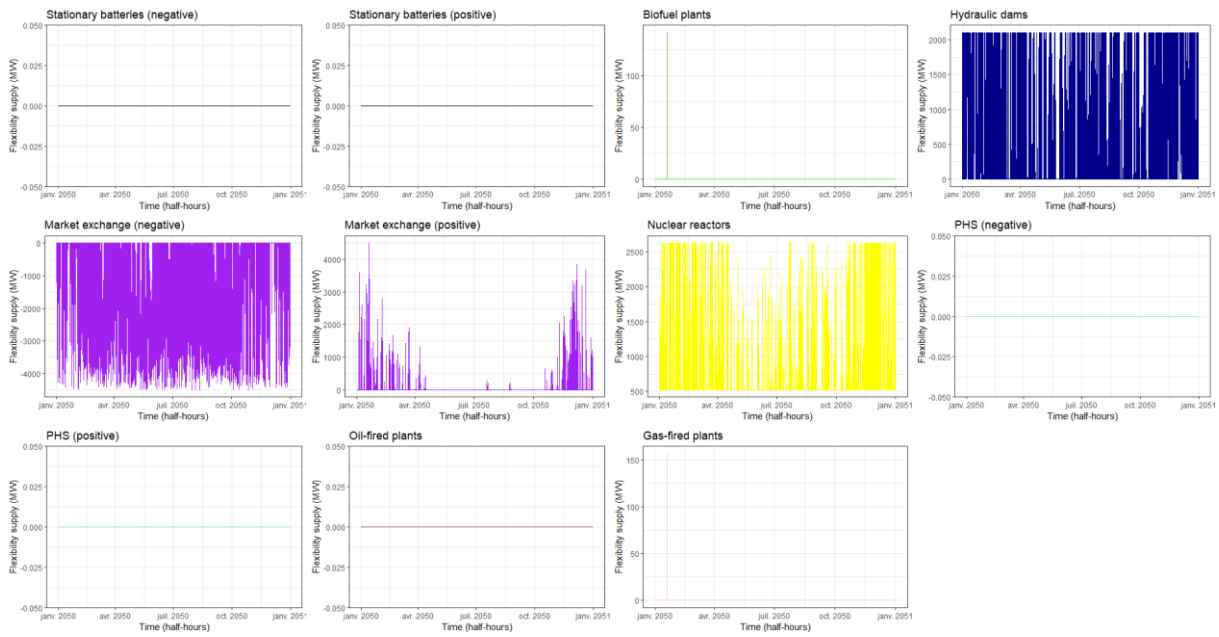


Figure 35 : Half-hourly production curves of flexible technologies in the *Intensive Electrification* scenario with *Constrained hydropower* parametrization

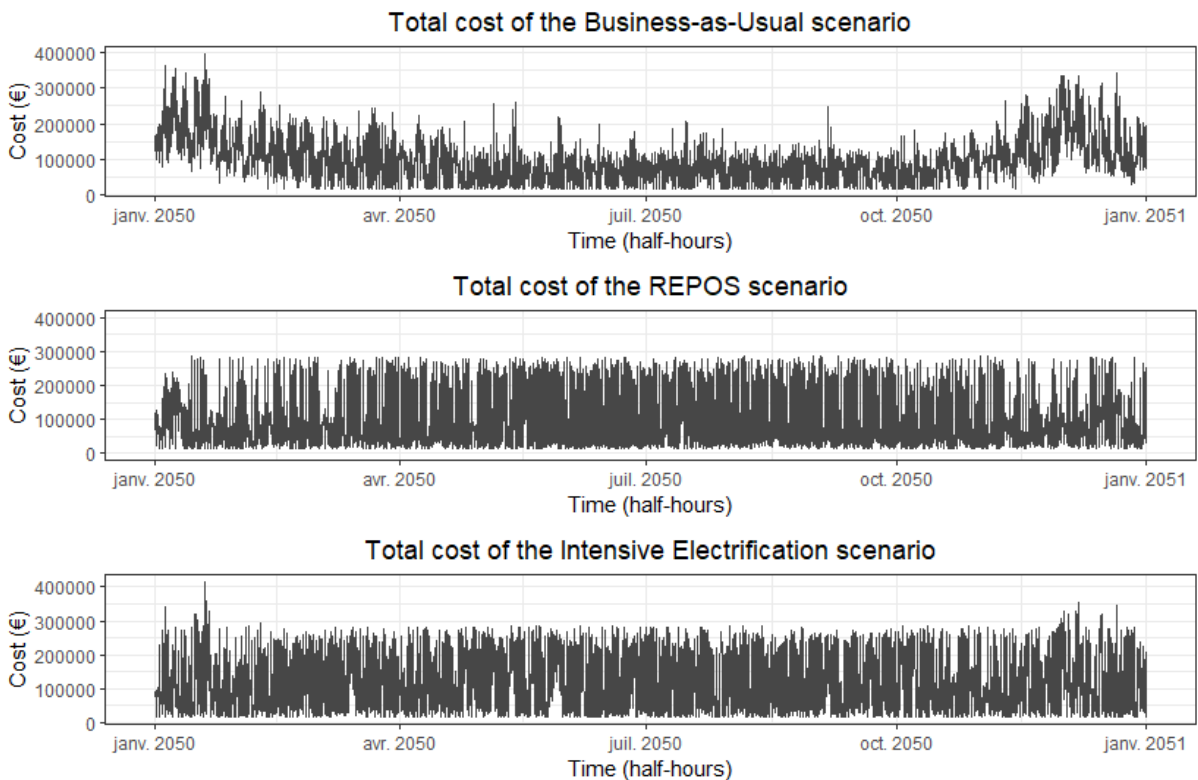


Figure 36 : Half-hourly total costs of the three considered scenarios with *Constrained hydropower* parametrization

E. Battery development results

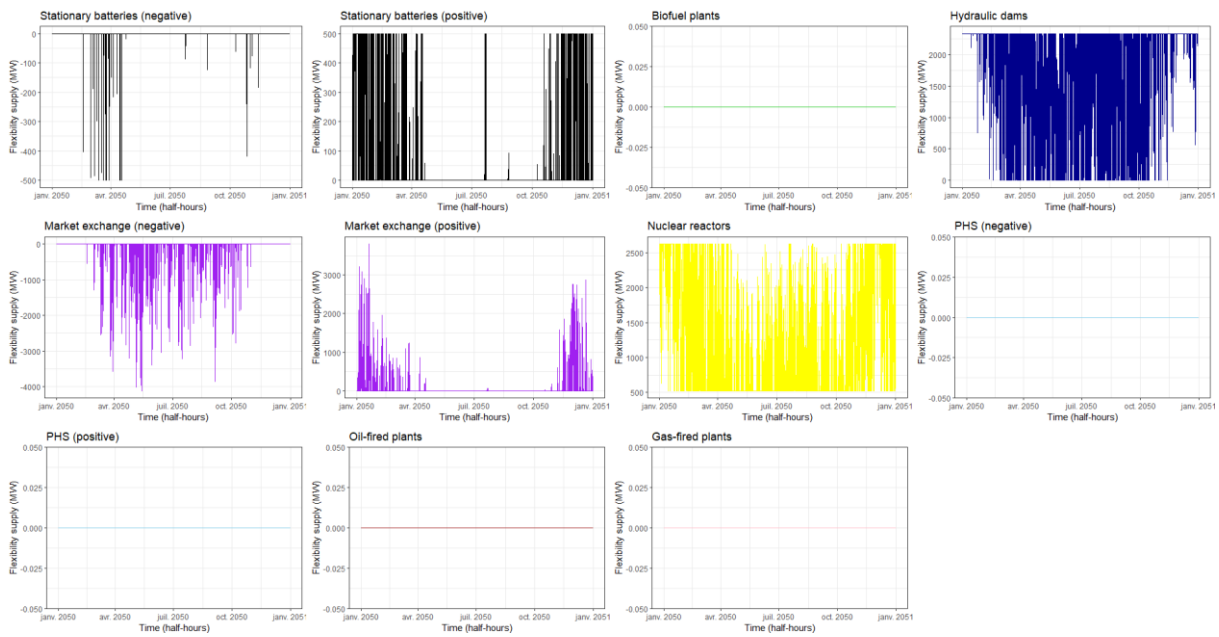


Figure 37 : Half-hourly production curves of flexible technologies in the *Business-as-Usual* scenario with *Battery development* parametrization

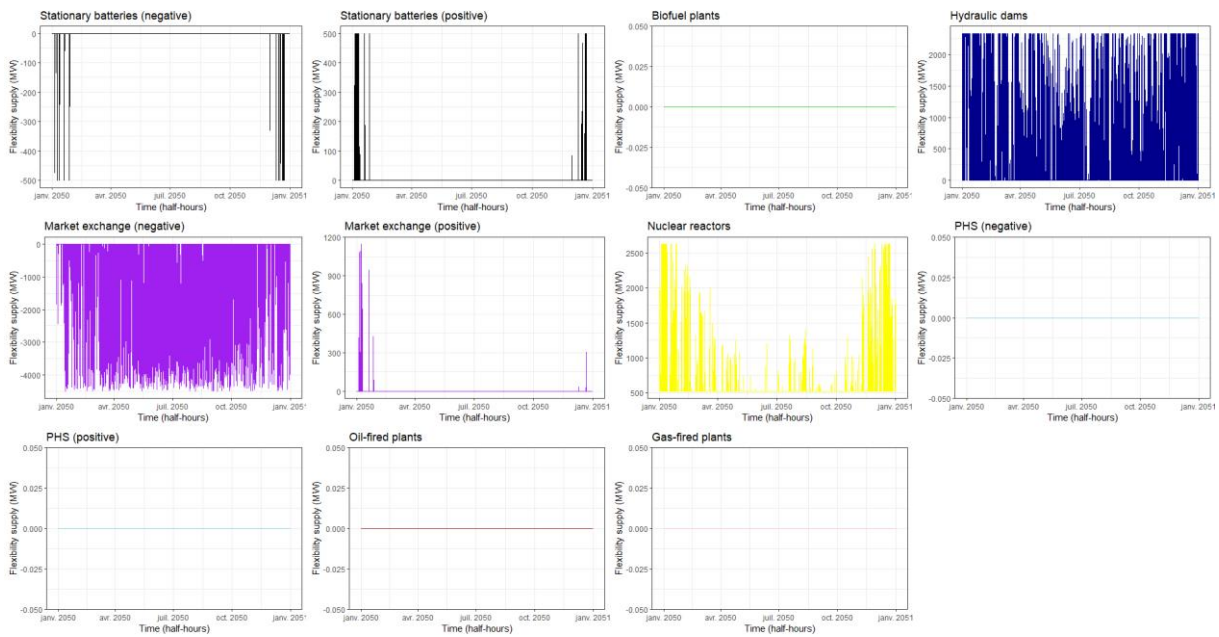


Figure 38 : Half-hourly production curves of flexible technologies in the REPOS scenario with *Battery development* parametrization

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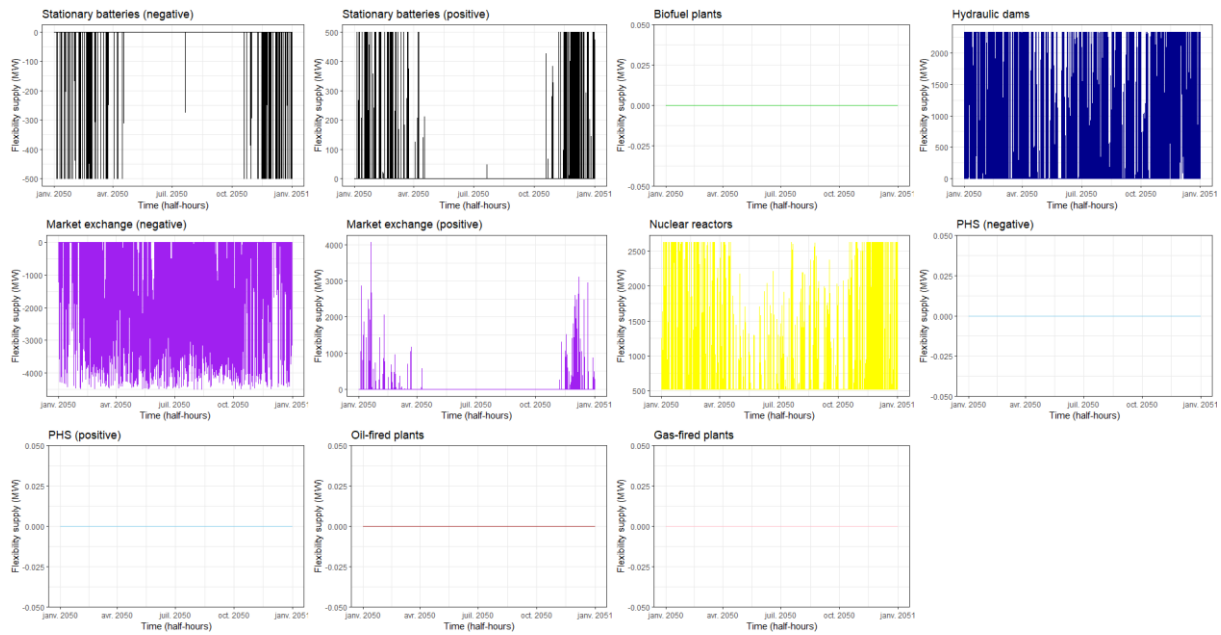


Figure 39 : Half-hourly production curves of flexible technologies in the *Intensive Electrification* scenario with *Battery development* parametrization

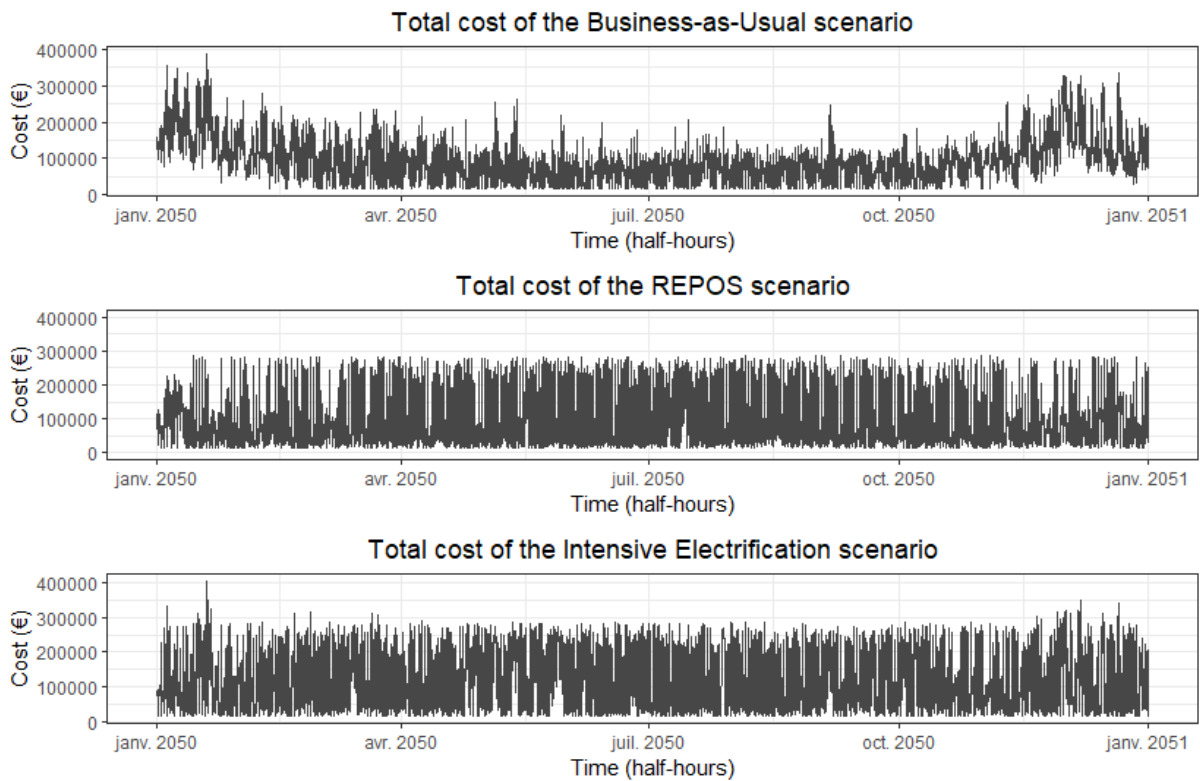


Figure 40 : Half-hourly total costs of the three considered scenarios with *Battery development* parametrization

## F. Fossil fuels exclusion results

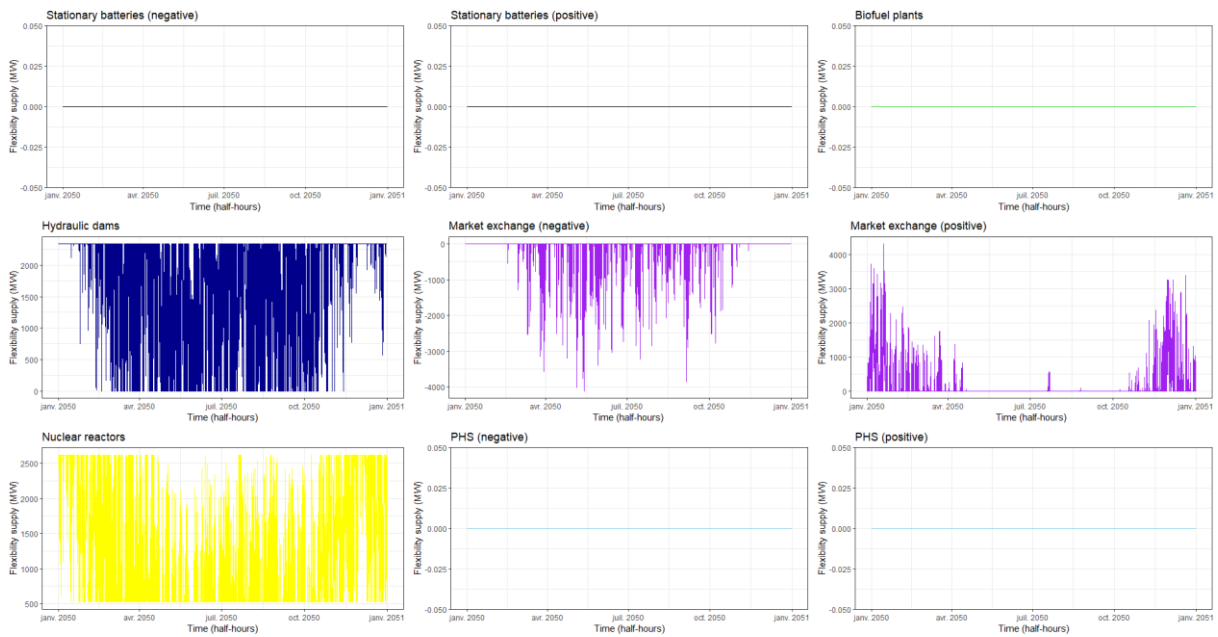


Figure 41 : Half-hourly production curves of flexible technologies in the *Business-as-Usual* scenario with *Fossil fuels exclusion* parametrization

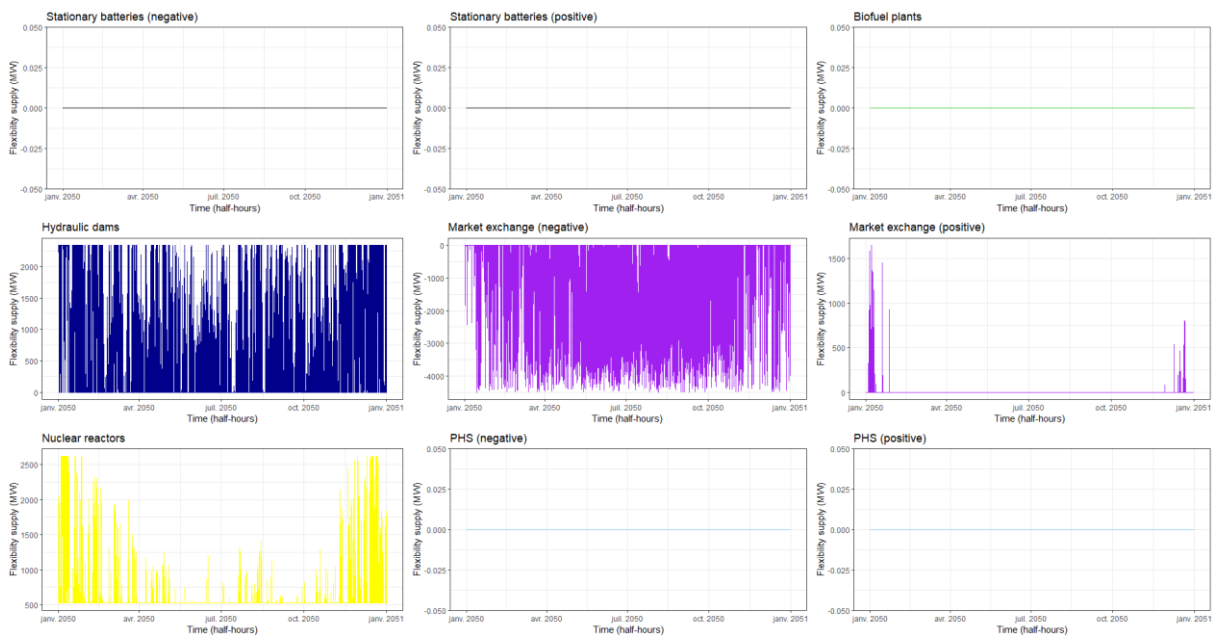


Figure 42 : Half-hourly production curves of flexible technologies in the REPOS scenario with *Fossil fuels exclusion* parametrization



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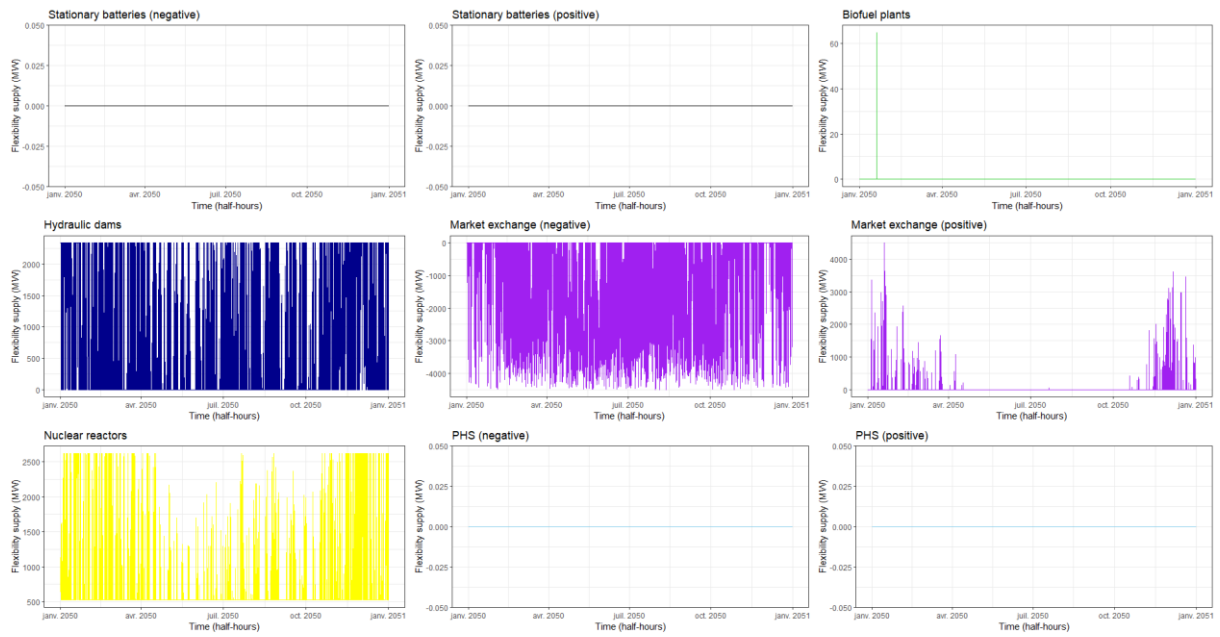


Figure 43 : Half-hourly production curves of flexible technologies in the *Intensive Electrification* scenario with *Fossil fuels exclusion* parametrization

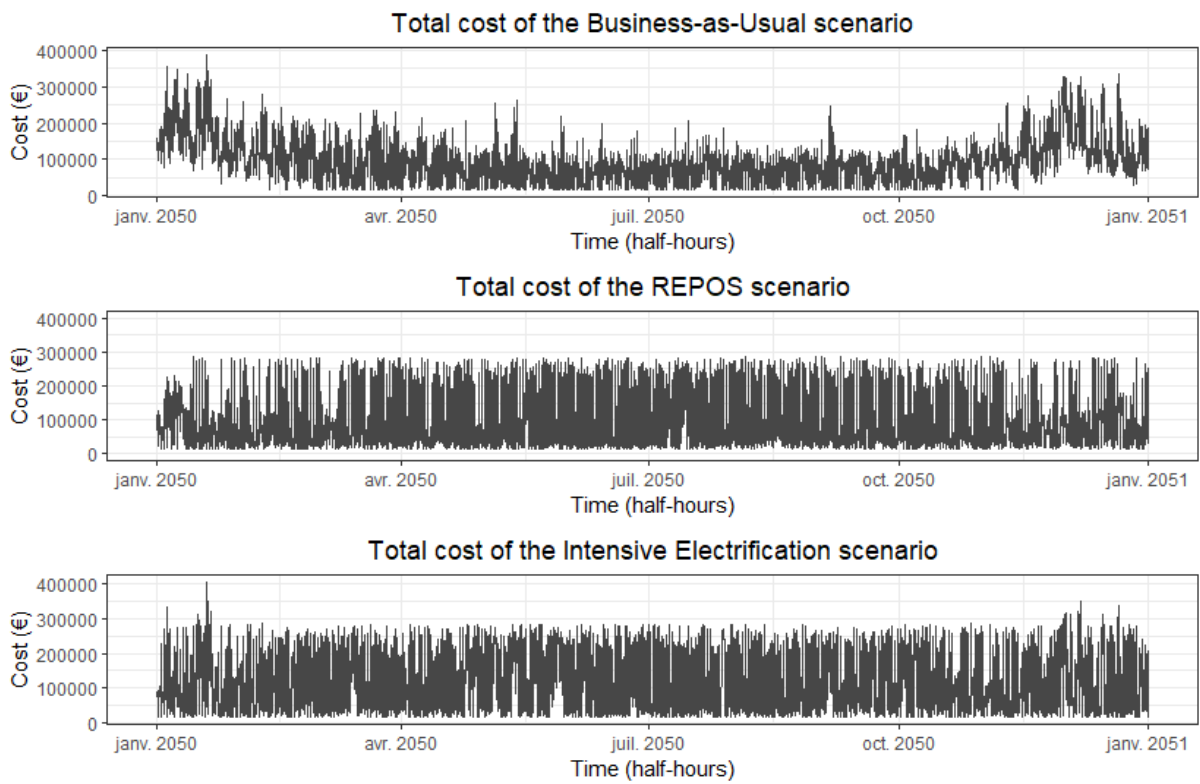


Figure 44 : Half-hourly total costs of the three considered scenarios with *Fossil fuels exclusion* parametrization





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# ENERGIES RENOUVELABLES INTERMITTENTES ET FLEXIBILITÉ DU SYSTÈME ÉLECTRIQUE : LE CAS DE LA RÉGION OCCITANIE

## VARIABLE AND RENEWABLE ENERGIES AND POWER SYSTEM FLEXIBILITY : THE CASE OF FRENCH REGION OCCITANIE

**Théotime COUDRAY**

**SOUS LA DIRECTION DE**

**Mme Sandrine MICHEL**

**Mr Boris SOLIER**

This thesis addresses the issue of power system flexibility within the context of the regional power system of Occitanie. We first develop a forecasting model to predict the flexibility requirements, and then propose an optimization based model of flexible capacities to address the requirements. Finally, we propose a set of scenarios for 2050, in which we explore various factors that might affect the requirements as well as the provision of flexibility within Occitanie region power system.

Cette thèse aborde la question de la flexibilité du système électrique dans le contexte du système électrique régional d'Occitanie. Nous développons d'abord un modèle de prévision pour prédire les besoins de flexibilité, puis nous proposons un modèle basé sur l'optimisation des capacités flexibles pour répondre aux besoins. Enfin, nous proposons un ensemble de scénarios pour 2050, dans lesquels nous explorons les différents facteurs qui pourraient affecter les besoins ainsi que la fourniture de flexibilité au sein du système électrique de la région Occitanie.

