HEC MONTRÉAL

La valeur de l’intégration régionale de l’hydroélectricité et sa robustesse à des coûts de stockage court terme décroissants : le cas de la décarbonation dans le nord-est de l’Amérique du Nord.

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Sciences de la gestion
(Spécialisation Économie Appliquée)

Mémoire présenté en vue de l’obtention
du grade de maîtrise ès sciences
(M. Sc.)

Avril 2022

Résumé

Depuis l'Accord de Paris, de nombreuses juridictions ont adopté des cibles de décarbonation ambitieuses pour leur secteur électrique (par exemple, zéro émission d'ici 2040 dans l'État de New York). L'intégration de grandes quantités d'énergie renouvelable intermittente, comme le solaire et l'éolien, soulève de nouveaux défis pour équilibrer l'offre et la demande. Le stockage devient particulièrement critique dans un tel contexte. La valeur d'autres ressources flexibles, telles que les réservoirs hydroélectriques existants combinés avec la transmission régionale, est cependant souvent négligée, d'autant plus que les options de stockage à court terme (telles que les batteries) deviennent de plus en plus accessibles. Sur la base d'un modèle d'expansion de capacité et de répartition du système électrique du nord-est de l'Amérique du Nord, nous estimons la valeur de l'hydroélectricité québécoise et des capacités d'interconnexion dans un scénario zéro émission pour la région. Nous évaluons également la robustesse des résultats aux variations des coûts de stockage à court terme ainsi qu'aux coûts de la capacité de transmission. Les résultats montrent que la combinaison réservoir-transmission diminue le coût de la décarbonation, même lorsque les coûts de stockage à court terme sont faibles. Toutefois, la distribution des coûts et des bénéfices est inégale entre les régions. Même à un coût d'investissement élevé, la transmission supplémentaire apporte de la flexibilité en diminuant considérablement le besoin de stockage à court terme et de gaz naturel renouvelable, puisque la transmission avec le Québec est utilisée à la fois pour l'équilibrage journalier et saisonnier.

Mots-clés : Transmission ; Stockage ; Hydroélectricité ; Décarbonation ; Nord-Est de l'Amérique du Nord

Méthode de recherche : Programmation mathématique

Abstract

Since the Paris Agreement, many jurisdictions have implemented significant decarbonization targets for their electric system (e.g. zero emissions by 2040 in the state of New York). The integration of large amounts of intermittent renewable energy, such as solar and wind, brings new challenges to balance demand and supply. Storage becomes especially critical in such context. The value of other flexible resources, such as existing hydropower with reservoir storage and regional transmission, is however often overlooked, especially since short-term storage options (such as batteries) are quickly becoming more accessible. Based on a capacity expansion and dispatch model of the Northeastern North American power system, we estimate the value of Quebec's hydropower and interconnection capacities under a zero- emission scenario for the region. We also assess the robustness of the results to variations in short duration storage costs as well as in transmission capacity costs. The results show that the reservoir-transmission coupling decreases the cost of decarbonization, even when short-term storage costs are low, although the distribution of costs and benefits is uneven among regions. Even at a high investment cost, additional transmission provides flexibility significantly decreasing the need for short-term storage and renewable natural gas, because transmission with Quebec is used both for daily and seasonal balancing.

Keywords : Transmission ; Storage ; Hydropower ; Decarbonization ; Northeastern North America

Research method : Mathematical programmation

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Avant-propos

Le chapitre 1 de ce mémoire reproduit intégralement un article rédigé en collaboration avec M. Justin Caron, professeur agrégé au département d'économie appliquée de HEC Montréal, et M. Pierre-Olivier Pineau, professeur titulaire au département des sciences de la décision de HEC Montréal.

Remerciements

Au terme de ce projet, je souhaiterais remercier mes directeurs de recherche MM. Justin Caron et Pierre-Olivier Pineau d'avoir accepté de m'encadrer et de m'avoir ainsi permis de travailler sur un sujet aussi passionnant. Merci pour tous vos conseils, votre disponibilité et votre générosité. Travailler à vos côtés aura été pour moi un grand plaisir.

J'aimerais également remercier mes proches, et en particulier Alexandre et Amaëlle, pour leur soutien et leurs encouragements.

Introduction générale

Dans le nord-est de l'Amérique du Nord, la plupart des gouvernements régionaux se sont engagés à réduire les émissions de gaz à effet de serre (GES) d'au moins 80 % par rapport aux niveaux de 1990 d'ici 2050 (Pineau et Langlois-Bertrand, 2020). Les marchés de l'électricité du Northeast Power Coordinating Council (NPCC) visent à réduire leur dépendance à l'égard des combustibles fossiles, en intégrant davantage de sources d'énergie renouvelables telles que le solaire et l'éolien dans leurs réseaux électriques. Par exemple, l'État de New York est tenu de produire de l'électricité sans émissions d'ici 2040 et chaque État de la Nouvelle-Angleterre a également adopté une norme de portefeuille renouvelable (Renewable Portfolio Standard), exigeant des utilités qu'une part minimale de l'électricité qu'ils vendent provienne d'énergies renouvelables, à des échéances déterminées (National Conference of State Legislatures, 2021).

L'intermittence de ces sources de production soulève toutefois des enjeux importants. Le stockage et les ressources flexibles deviennent particulièrement critiques dans un tel contexte. Cependant, plusieurs visions semblent s'opposer (Penn et Krauss, 2021). Certains défendent l'idée que le stockage et les ressources décentralisées sont la solution, tandis que d'autres préfèrent miser sur les investissements en transmission et une plus grande coordination entre les juridictions.

Au fil des années, un grand nombre d'études se sont intéressées au rôle du stockage dans la décarbonation des réseaux électriques et constatent que le stockage d'énergie permet de réduire le coût de production de l'électricité et d'intégrer davantage de solaire et d'éolien (Liu et collab., 2019; de Sisternes et collab., 2016). En particulier, le stockage d'énergie longue durée (plus de 10h) permet d'augmenter la proportion d'énergie éolienne (de Sisternes et collab., 2016) alors que le stockage courte durée (2h) permet d'introduire plus de solaire (Pfeifenberger et Lueken, 2019; Liu et collab., 2019). Le stockage électrique permet de diminuer les prix pendant les heures de pointe tout en soutenant les prix des heures creuses (Pfeifenberger et Lueken, 2019) Il contribue également à réduire le plafonnement éolien et solaire ainsi que la participation des combustibles fossiles (de Sisternes et collab., 2016). Par ailleurs, le stockage distribué permet de reporter ou d'éviter des investissements dans les infrastructures de distribution et de transmission (Pfeifenberger et Lueken, 2019; Liu et collab., 2019). Néanmoins, la littérature semble convenir de la nécessité de réduire les coûts des batteries de stockage pour justifier un déploiement à grande échelle (Brinkman et collab., 2021b; de Sisternes et collab., 2016). En outre, Jorgenson et collab. (2018) affirment que la valeur du stockage dépend de la transmission, dans la mesure où elle augmente avec l'augmentation de la capacité de transmission en raison notamment de la diminution de la congestion et d'une meilleure aptitude à décharger pendant les périodes où les prix sont les plus élevés. Ce résultat semble être en contradiction avec celui de Dolter et Rivers (2018) qui constatent que les nouvelles lignes de transmissions effacent le besoin d'installer des systèmes de stockage d'énergie. Cela démontre que la valeur et le rôle du stockage ne sont pas encore clairement établis.

Par ailleurs, Sepulveda et collab. (2021) étudient le rôle du stockage de longue durée dans la décarbonation des systèmes électriques et les caractéristiques lui permettant de faire baisser les coûts de l'électricité. Ils constatent que les systèmes de stockage d'une durée supérieure à 100 heures ont la plus grande influence sur les coûts du système, et que le coût de l'énergie du stockage est un paramètre déterminant pour parvenir à une diminution des coûts à l'échelle du système. Plus précisément, ils constatent que le coût d'investissement du stockage doit être inférieur à 20 $/kWh pour réduire d'au moins 10 % les coûts de décarbonation du système. Cependant, dans leur étude, ils considèrent uniquement des systèmes de stockage nécessitant des investissements importants, comme la réserve pompée ou le stockage d'énergie à air comprimé, et ne considèrent pas les réservoirs hydroélectriques existants comme une ressource de stockage de longue durée. Pourtant, dans certaines régions, comme le Québec, ces installations sont déjà disponibles sans coût supplémentaire. Par exemple, Hydro-Québec annonce disposer de 176 TWh de stockage disponible dans les réservoirs de son réseau, soit plus que la consommation annuelle actuelle de New York (Hydro-Québec, 2022). Il ne manque actuellement que la transmission et une structure de marché appropriée pour mieux valoriser ces ressources de stockage longue-durée.

De plus, des études récentes montrent que les réservoirs hydroélectriques existants sont en mesure d'équilibrer l'intermittence éolienne et solaire à un coût bien inférieur à celui des autres ressources (Rodríguez-Sarasty et collab., 2021; Aubin et collab., 2021; Graabak et collab., 2017). Ils montrent que l'accès à l'hydroélectricité permet d'accélérer la décarbonation, en diminuant notamment la production à partir du gaz naturel de 80% à 90% dans des scénarios de décarbonation partielle du système électrique de 80% à 90% (Brinkman et collab., 2021a).

Certaines de ces études ont également examiné l'impact de la croissance de la capacité de transmission vers les réservoirs hydroélectriques du Québec sur la décarbonation du Nord-Est (Rodríguez-Sarasty et collab., 2021; Aubin et collab., 2021; Brinkman et collab., 2021a,b; Dimanchev et collab., 2021). Plus précisément, Dimanchev et collab. (2021) ont constaté que les réservoirs hydroélectriques ont le potentiel de servir de ressource de stockage d'énergie à court et à long terme (et même de stockage annuel), réduisant ainsi le besoin d'autres ressources d'équilibrage telles que la captation carbone. Dolter et Rivers (2018); Brown et Botterud (2021) arrivent également à des conclusions similaires.

Par ailleurs, la valeur de la transmission dans la décarbonation des systèmes électriques est également une source de grand intérêt. En particulier, plusieurs études constatent qu'une coordination et une capacité de transmission accrues réduisent la fréquence du plafonnement et fournissent des services d'équilibrage grandement valorisés (EIA, 2018; Rodríguez-Sarasty et collab., 2021; Dolter et Rivers, 2018; Brinkman et collab., 2021a,b; Brown et Botterud, 2021). Par conséquent, la transmission supplémentaire permet de réduire les coûts à l'échelle du système (Rodríguez-Sarasty et collab., 2021; Dolter et Rivers, 2018; Brown et Botterud, 2021). Plus précisément, elle fait diminuer les besoins d'investissement en nouvelle capacité de production (Rodríguez-Sarasty et collab., 2021; Brown et Botterud, 2021). De plus, selon Rodríguez-Sarasty et collab. (2021); Dolter et Rivers (2018); Brown et Botterud (2021), les nouvelles lignes de transmission réduisent également la quantité de stockage nécessaire. Par conséquent, Dolter et Rivers (2018) concluent que le stockage et la transmission sont manifestement des substituts. Par ailleurs, étant donné que les investissements dans de nouvelles lignes de transmission favorisent une plus grande pénétration de l'énergie éolienne, leur utilisation est beaucoup plus importante et par conséquent souvent bidirectionnelle (Rodríguez-Sarasty et collab., 2021; Brinkman et collab., 2021a,b).

Bien que de nombreuses études s'accordent à dire que la transmission ou les ressources de stockage peuvent réduire les coûts du système, très peu d'articles étudient la répartition des coûts et des bénéfices entre les différents participants. Rodríguez-Sarasty et collab. (2021) constatent que les coûts et les bénéfices ne sont pas répartis équitablement entre les régions. Par exemple, avec de nouvelles lignes de transmission, le Québec subit des prix beaucoup plus élevés sur son territoire alors que la Nouvelle-Angleterre et New York, bien que bénéficiant d'un plus grand accès aux réservoirs québécois, bénéficient de prix beaucoup plus faibles, dans un contexte de décarbonation profonde. Parallèlement, Aubin et collab. (2021) soulignent que la structure actuelle du marché de l'électricité n'incite pas à une participation optimale de l'hydroélectricité québécoise. Cependant, ces études se concentrent sur les effets sur les coûts d'investissement et les coûts d'exploitation, et n'étudient pas en détail l'effet sur la balance commerciale des régions ou sur le surplus global.

Pour réaliser ce mémoire, le modèle d'expansion de capacité et de répartition développé par Rodríguez-Sarasty et collab. (2021) a été utilisé. Le mémoire évalue la capacité de la combinaison réservoir-transmission (c'est-à-dire avoir des lignes de transmission donnant accès aux réservoirs hydroélectriques) à remplacer le besoin de nouvelles installations de stockage de courte durée (avec une capacité de stockage cyclique quotidienne) et de gaz naturel renouvelable. De plus, lorsque les réservoirs hydroélectriques sont disponibles, leur valeur, qui est définie comme le gain de surplus procuré à la décarbonation du système (ce qui équivaut à une réduction des coûts pour l'ensemble de la région), augmente considérablement avec les capacités de transmission vers d'autres régions. Par ailleurs, ce travail fournit une analyse de sensibilité, qui permet de déterminer la robustesse de la valeur de la transmission à un faible coût de stockage court terme. Ainsi, il est démontré que la valeur de la transmission n'est pas compromise par la disponibilité d'un stockage court terme abordable, notamment car elle sert à l'équilibrage saisonnier. Inversement, la valeur du stockage à court terme diminue avec la disponibilité d'une transmission peu coûteuse, puisque la transmission peut également fournir des services d'équilibrage journalier. Enfin, le modèle permet d'analyser la répartition de l'effet des nouvelles lignes de transmission entre les sous-régions sur la balance commerciale ainsi que sur le surplus régional et global. Ainsi, il apparaît que les coûts et les avantages ne sont pas répartis de manière égale entre les sous-régions, certaines sous-régions connaissant des gains de surplus tandis que d'autres subissent des pertes.

Le Chapitre 1 reproduit l'intégralité de l'article intitulé « The value of regional Hydropower Integration and robustness to decreasing Short-term Storage costs : the case of Decarbonization in Northeastern North America », qui a été rédigé dans le cadre de ce mémoire. L'introduction de l'article est suivie par une présentation de la méthodologie et des données utilisées (section 1.2). Les résultats de l'article sont ensuite décrits dans la section 1.3. Les conclusions et implications politiques suivent dans la section 1.4. Enfin, le mémoire se termine avec une conclusion générale relatant les principales conclusions de l'article.

Chapitre 1

The value of regional Hydropower Integration and robustness to decreasing Short-term Storage costs : the case of Decarbonization in Northeastern North America

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April 2022

Since the Paris Agreement, many jurisdictions have implemented significant decarbonization targets for their electric system (e.g. zero emissions by 2040 in the state of New York). The integration of large amounts of intermittent renewable energy, such as solar and wind, brings new challenges to balance demand and supply. Storage becomes especially critical in such context. The value of other flexible resources, such as existing hydropower with reservoir storage and regional transmission, is however often overlooked, especially since short-term storage options (such as batteries) are quickly becoming more accessible. Based on a capacity expansion and dispatch model of the Northeastern North American power system, we estimate the value of Quebec's hydropower and interconnection capacities under a zero-emission scenario for the region. We also assess the robustness of the results to variations in short duration storage costs as well as in transmission capacity costs. The results show that the reservoir-transmission coupling decreases the cost of decarbonization, even when short-term storage costs are low, although the distribution of costs and benefits is uneven among regions. Even at a high investment cost, additional transmission provides flexibility significantly decreasing the need for short-term storage and renewable natural gas, because transmission with Quebec is used both for daily and seasonal balancing.

Keywords : Transmission ; Storage ; Hydropower ; Decarbonization ; Northeastern North America

1.1 Introduction

In Northeastern North America most regional governments have committed to reducing greenhouse gas (GHG) emissions to at least 80% below 1990 levels by 2050 (Pineau and Langlois-Bertrand, 2020). Electricity markets in the Northeast Power Coordinating Council (NPCC) aim to reduce their fossil fuel reliance, with an increasing share of renewable energy sources such as solar and wind within their power systems. For instance, New York state is required to achieve zero-emission electricity by 2040 and each New England states has also adopted Renewable Portfolio Standard, requiring utilities to have a minimum share of the electricity they sell sourced from renewable energy, by specified dates (National Conference of State Legislatures, 2021).

Nevertheless, the intermittency of these generation sources brings major issues. Storage and flexible resources become especially critical in such context. However, several strategies seem to be in opposition (Penn and Krauss, 2021). Some advocate that storage and decentralized resources are the solution, while others would rather rely on transmission investments and greater coordination among jurisdictions.

Over the years, many have been interested in the role of energy storage in the decarbonization of power systems. They find that energy storage allows reduced electricity generation cost and a greater integration of solar and wind (Liu et al., 2019; de Sisternes et al., 2016). Above all, longer-duration energy storage (over 10h) increases the share of wind power (de Sisternes et al., 2016) whereas short-duration storage (2h) helps introduce more solar (Pfeifenberger and Lueken, 2019; Liu et al., 2019). Energy storage also leads to reducing peak hour prices while supporting off-peak prices (Pfeifenberger and Lueken, 2019) and reduces curtailment of wind and solar and the contribution from fossil fuel (de Sisternes et al., 2016). Moreover, distributed storage enables deferral or avoidance of investments in distribution and transmission infrastructure (Pfeifenberger and Lueken, 2019; Liu et al., 2019). Nevertheless, the literature seems to agree that cost reductions in battery storage are needed to justify large-scale deployment (Brinkman et al., 2021b; de Sisternes et al., 2016). Furthermore, Jorgenson et al. (2018) state that the value of storage is transmission-dependent as it increases with increased transmission capacity due to reduced congestion and greater ability to discharge during periods of highest prices. This result appears to be at odds with that of Dolter and Rivers (2018) who find that new transmission obviate the need to build energy storage systems. This demonstrates that the value and role of storage are not yet clearly established.

Furthermore, Sepulveda et al. (2021) investigate the role of long-duration storage in decarbonizing power systems and the characteristics that allow it to reduce electricity costs. They find that storage systems with duration over 100 hours have the biggest influence on system costs, and that the energy capacity cost of storage is a leading performance parameter to achieve systemwide cost reduction. Specifically, they find that energy capacity costs must fall below $20/kWh to reduce system decarbonization costs by at least 10%. Nevertheless, in their study, they only consider storage systems that require significant investments, like pumped hydro storage or compressed air energy storage, and do not consider existing hydro reservoirs as a long-duration storage resource. Yet in some regions, such as Quebec, these facilities are already available at no additional cost. For instance, Hydro-Québec announces 176 TWh of available storage in its system of reservoirs, more than the current yearly consumption of New York (Hydro-Québec, 2022). Only transmission and appropriate market structure are still lacking.

In addition, previous studies show that existing hydro reservoirs have the potential to balance wind and solar intermittency at a much lower cost than other ressources (Rodríguez-Sarasty et al., 2021; Aubin et al., 2021; Graabak et al., 2017). They show that access to hydropower can accelerate decarbonization, by reducing gas generation by 80% to 90% under partial decarbonization of the power system scenarios with GHG emission reductions of 80% to 90%. (Brinkman et al., 2021a).

Some of these studies have also looked at the impact of expanding transmission access to Quebec hydro reservoirs in decarbonizing the Northeast (Rodríguez-Sarasty et al., 2021; Aubin et al., 2021; Brinkman et al., 2021a,b; Dimanchev et al., 2021). More specifically, Dimanchev et al. (2021) found that hydro reservoirs have the potential to serve as both short and long-term energy storage resource (even as annual storage), thus reducing the need for other balancing resources such as Carbon Capture and Storage. Dolter and Rivers (2018); Brown and Botterud (2021) also reach similar conclusions.

Moreover, the value of transmission in the decarbonization of power systems is also a source of significant interest. In particular, several studies find that increased coordination and transmission reduce occurrence of curtailment and provide valuable balancing services (EIA, 2018; Rodríguez-Sarasty et al., 2021; Dolter and Rivers, 2018; Brinkman et al., 2021a,b; Brown and Botterud, 2021). Therefore, additional transmission reduces system-wide costs (Rodríguez-Sarasty et al., 2021; Dolter and Rivers, 2018; Brown and Botterud, 2021). More specifically, it reduces the need to invest in new generation capacity (Rodríguez-Sarasty et al., 2021; Brown and Botterud, 2021). Moreover, according to Rodríguez-Sarasty et al. (2021); Dolter and Rivers (2018); Brown and Botterud (2021), new transmission lines also reduce the amount of required storage. Hence, Dolter and Rivers (2018) conclude that storage and transmission are clear substitutes. As investments in new transmission leads to wider penetration of wind power, utilization rates of transmission lines are much higher and they are therefore often used bidirectionally (Rodríguez-Sarasty et al., 2021; Brinkman et al., 2021a,b).

Although many studies agree that transmission or storage resources can lower system costs, very few articles investigate the cost and benefit allocation among the different participants. Rodríguez-Sarasty et al. (2021) finds that the costs and benefits are not evenly shared between regions. For instance, with new transmission lines Quebec experiences much higher costs on its territory whereas New England and New York, despite benefitting from a greater access to hydropower reservoir storage, experience much lower costs, under deep decarbonization. Similarly, Aubin et al. (2021) highlight that the current electricity market structure does not provide incentives for an optimal contribution of Quebec hydropower. However, these studies focus on the effect on investment and operating costs, and do not fully investigate the effect on the trade balance of the regions or on the overall surplus.

To conduct our study, we used the capacity expansion and dispatch model developed by Rodríguez-Sarasty et al. (2021). This study contributes to the literature in three main ways. First, this article assesses the ability of the reservoir-transmission coupling (i.e., having transmission lines that provide access to hydro reservoirs) to replace the need for new short duration storage facilities (with daily cyclic storage capacity, i.e., energy charged must equal energy discharged over a day) and renewable natural gas. Also, when hydro reservoirs are available, their value, which we define as the surplus gains they bring in decarbonizing the system (which equals cost reductions for the overall region), increases substantially with transmission capacities to other regions. Second, this paper provides a sensitivity analysis, which allows us to address the robustness of the value of transmission to low short duration storage cost. Thus, showing that the value of transmission is not compromised by the availability of affordable short-term storage, as it also serves an important role in seasonal balancing. Conversely, the value of short-term storage is compromised by the availability of inexpensive transmission, since transmission can also provide daily balancing services. Finally, our model allows us to analyze the distribution of the effect of new transmission lines across sub-regions on the trade balance as well as on the regional and overall surplus. Thus, it appears that costs and benefits are not evenly distributed across sub-regions, with some sub-regions experiencing surplus gains while others are suffering losses.

This paper is organized as follows. The methodology and data are presented in the subsequent section. Results are then described in section 1.3 General conclusions and policy implication follow in section 1.4

1.2 Data and Methodology

1.2.1 Model overview

The model determines the optimal portfolio of investments in generation capacity, transmission lines and energy storage as well as the hourly dispatch of generation resources to meet electricity demand and reach specific decarbonization goals. The model minimizes the total annualized costs of investment and operation. The hourly data over a representative year (8,760 time steps) allows us to capture the intermittency of renewable technologies along with the inter-temporal effects of hydropower reservoirs. A complete description of the model can be found in Rodríguez-Sarasty et al. (2021). As described by Rodríguez-Sarasty et al. (2021), the model includes operational constraints for hourly power balance, capacity requirements, power exchanges, carbon emissions, demand response and load shedding (which can be used to reduce power demand when electricity prices are high or generation capacity is insufficient), and limited expansion potential of carbon-free power technologies. Some of the data underlying the original model as well as the assumptions we revised are discussed in the following subsection, with further information in Appendix A.

1.2.2 Data

The geographic scope of the study is Northeastern North America, which covers the Canadian provinces of Quebec (QC), Ontario (ON), and four Atlantic provinces (AT), [1] as well as New York (NY) state and the six New England (NE) states [2] in the United States. All jurisdictions are

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[1] New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland and Labrador.

[2] Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont.

assumed to pursue strong decarbonization of their economies, including complete decarbonization of their electricity grids. Therefore, the hourly load in New York is generated using the 2018 profile and NYISO seasonal peak growth factor forecasts (NYISO, 2021) under its decarbonization scenario, where electrification of heating and transport induce different changes in load profile. New England load profile is then estimated using the same seasonal peak growth assumptions as for New York. It results in a total energy growth factor of 1.5 and a power peak switching from summer to winter. The Ontario load profile is derived by adjusting the 2018 profile to account for IESO forecasts (IESO, 2020). For Quebec and the Atlantic provinces, a growth factor of 1.1 was applied to their 2018 load profiles as Hydro-Québec Distribution (2019) and NB Power (2019) are expecting an average annual growth rate well under 1% by 2030. Details of regional load profiles are shown in Table A.1.

Furthermore, the New England Clean Energy Connect (NECEC) transmission line connecting Quebec and New England would cost about \$800k/MW (New England Clean Energy Connect, 2021) while the Champlain Hudson Power Express Line project linking Quebec and New York would cost around \$2.4M/MW according to some estimations (Independent Power Producers of New York, 2021). Thus, we decided to use an investment cost of \$1M/MW for new transmission lines, irrespective of distance,[3] but also conduct a sensitivity analysis over this transmission cost.

The energy storage options included in the model are pumped hydro storage and short-duration electrical storage with an assumed daily cyclic storage capacity (energy charged must equal energy discharged within a day). However, the short-term storage costs estimated by NREL (2021) span a wide range, from \$205k/MW to over \$3M/MW. The EIA (2021) estimates storage costs of around \$1.2M/MW. Thus, in our study, we use a \$1.4M/MW capital cost for storage. This investment cost, over 10 years, comes to \$177.4k per MW-year when using a 6% discount rate. Therefore, our robustness analysis appears all the more relevant as it allows us to consider this high dispersion of storage cost estimates.

The model includes two natural gas technologies : Combined Cycle Gas Turbines (CCGT) and Simple Combustion Turbines (CT), whose costs and parameters are presented in Table A.2. Since we only consider full decarbonization scenarios, the use of conventional natural gas plants is excluded. Carbon-neutral natural gas generation is allowed, but at a much higher operational cost than conventional generation. The latter represents either the use of carbon-neutral fuel or

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[3] In the region, all major links we are considering are about the same length.

the integration of a carbon capture and storage system into conventional gas plants. As explained by Rodríguez-Sarasty et al. (2021), based on a natural gas price of $3/MBtu, and a biomethane price of $14.5/MBtu, a first block of carbon-neutral natural gas capacity (up to 50 TWh) is defined with a fuel cost five times higher than conventional natural gas. A second block (up to 250 TWh) is defined with a fuel cost five times higher than the first one. The parameters of carbon-neutral natural gas are presented in Table A.3.

In addition, three categories of hydropower facilities were modelled : run-of-river facilities with no storage capacity, intra-day reservoirs with daily cyclic storage capacity and large reservoirs with yearly cyclic storage capacity. As hydropower facilities with intra-day or large reservoirs serve as flexible resources, water can be stored for future time periods, but it doesn't include pumped hydro storage facilities. In each sub-region, similar facilities have been aggregated, except for Quebec where the main hydropower facilities and their water flow interdependencies were modelled. Further details on hydropower modelling can be found in Rodríguez-Sarasty et al. (2021).

1.2.3 Scenarios and sensitivity to storage and transmission costs

To assess the value of hydropower reservoir and transmission and its relationship with short-term storage, we focus on Quebec because hydropower is the main electricity source and the capacity of hydro reservoirs in the other sub-regions is relatively small when compared to Quebec. We proceed with a comparative analysis of two scenarios. The first, which is referred to as the constrained transmission scenario, is one in which no new transmission capacity can be installed between Quebec and the other sub-regions. There are no constraints on transmission investment between Ontario, the Atlantic provinces, New York and New England. The second scenario, the optimal transmission scenario, enables unrestricted investment in additional transmission capacity with Quebec as well. Furthermore, in order to isolate the value of hydro reservoirs, no investment in solar nor in wind power in Quebec is allowed. Thus, if new transmission lines are installed in Quebec, it would only be to benefit from Quebec's hydropower. We then run sensitivity analysis by varying transmissions costs, holding all other costs constant, and varying storage costs, holding all other costs constant. We also compare the additional installed capacity as a function of storage cost and as a function of transmission cost, which allows us to evaluate the impact of transmission cost variations on the demand for additional power capacity. Furthermore, in section 1.3.4, to highlight the impact of storage cost on the whole region, we focus on the impact of relaxing the transmission capacity investment constraint in two very contrasting situations : when storage is free and when it is very expensive (with an annualized investment cost higher than $320k/MW-year). Hence, this allows us to assess the robustness of the value of transmission to short duration storage cost variations.

1.3 Results

To better assess the value of the transmission-reservoir coupling, we first present the overall results of the model, and then we address the specific results in sections 1.3.4 and 1.3.5.

1.3.1 Additional generation capacity and new transmission lines

Additional installed capacity in each sub-region is shown in Table 1.1 below. In the constrained transmission scenario, to achieve 100% decarbonization, 136.8 GW of new generation capacity is required, including 51.8 GW of solar, 79.4 GW of wind, 4.3 GW of storage and 0.9 GW of natural gas, an 87% increase relative to the overall initial installed capacity of 157.3 GW.

	QC	ON	AT	NY	NE	Total
Solar	-	2.3	-	31.9	17.6	51.8
Wind	-	6.7	13.8	22.9	35.9	79.4
Hydro	-	-	-	0.5	-	0.5
Storage	-	-	0.6	3.6	-	4.3
Gas CCGT	-	-	-	-	0.9	0.9
Total	-	9.0	14.5	58.9	54.4	136.8

(a) Constrained transmission

	QC	ON	AT	NY	NE	Total
Solar	-	1.3	0.5	32.7	16.7	51.3
Wind	-	5	13.8	22.9	34.8	76.5
Hydro	0.1	-	-	0.5	-	0.6
Storage	-	-	-	0.5	-	0.5
Gas CCGT	-	-	-	-	-	-
Total	-	6.3	14.3	56.1	51.5	128.8

(b) Optimal transmission

TABLE 1.1 – Additional generation capacity in GW per technology, sub-region and scenario.

In the optimal transmission scenario, a total of 128.8 GW of new capacity is installed across the region, a 6% reduction compared to the constrained transmission scenario. But, unlike the constrained transmission scenario, there is substantially less storage installed at only 0.5 GW and no additional gas capacity is required. By integrating Quebec's hydropower, there is less additional generation capacity installed, especially a 4% decrease of wind at 76.5 GW. The solar capacity added across the region remains relatively unchanged from the constrained to the optimal transmission scenario. However, the locations where it is installed differ. Indeed, additional solar capacity in Ontario and New England are lower than in the constrained transmission scenario by 42% and 5% respectively, while in New York and in the Atlantic provinces additional solar capacity is higher than in the constrained transmission scenario. This suggests that new transmission lines with Quebec can reduce the investment required in new generation capacity, including storage.

Table 1.2 presents the additional bilateral transmission capacity installed between the sub-regions under each scenario. It reveals that allowing new transmission lines with Quebec results in an increase of 4.1 GW of newly installed transmission capacity for the whole region, which corresponds to a 21% increase compared to the constrained transmission scenario. It can also be observed that each of the sub-regions will build new transmission lines with Quebec, for about 16.1 GW overall. In contrast, the added transmission capacity between the other sub-regions falls from 19.4 GW to 7.4 GW, representing a 62% decrease.

	NY	NE	Total
ON	9.8	-	9.8
AT	-	5.1	5.1
NY	-	4.6	4.6
Total	9.8	9.6	19.4

(a) Constrained transmission

	QC	ON	NY	NE	Total
ON	1.6	-	-	-	1.6
AT	2.7	-	-	2.8	5.5
NY	6.9	3.8	-	-	10.7
NE	4.9	-	0.9	-	5.8
Total	16.1	3.8	0.9	2.8	23.5

(b) Optimal transmission

TABLE 1.2 – Additional transmission capacity in GW between sub-regions.

In addition, under the optimal scenario, the transmission capacity added in New York and New England is significantly smaller than under the constrained scenario. For New York and New England, increasing transmission capacity with Quebec therefore means avoiding significant costs of both new generation capacity and new transmission capacity.

The overall addition of 23.5 GW of transmission capacity in the optimal scenario suggests that to successfully decarbonize the entire region, the overall transmission capacity between the sub-regions will be required to more than double from the current level of 22 GW.

1.3.2 Electricity trade

Looking at energy flows across the Northeast, as detailed in Table 1.3, it appears that energy imports from Quebec to the Atlantic provinces, New York and New England rise by 25%, 229% and 113% respectively, while trade from Quebec to Ontario falls by 60%. Also, every other sub-region increases its exports to Quebec by between 4% and 196%. On the contrary, trade between Ontario, the Atlantic provinces, New York and New England decline from 32% to 69% regardless of the direction. Thus, it seems that the other sub-regions reduce trade among themselves while increasing that with Quebec.

The increase in trade with Quebec from the constrained to the optimal scenario, as well as the strong decrease in newly installed storage and renewable gas capacity, suggests that increased trade with Quebec is used to balance the additional variable generation capacity installed, particularly in New York and New England.

	QC	ON	AT	NY	NE	Total
QC	-	10.3	3.7	8.8	9.2	32.1
ON	7.0	-	-	31.7	-	38.7
AT	3.1	-	-	-	13.6	16.6
NY	3.7	4.3	-	-	6.3	14.3
NE	7.8	-	5.1	13.6	-	26.5
Total	21.6	14.7	8.9	54.1	29.0	128.2

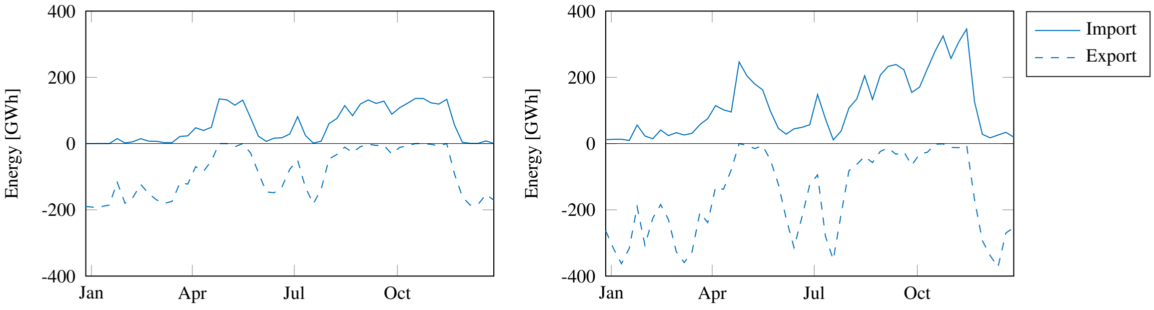
(a) Constrained transmission

	QC	ON	AT	NY	NE	Total
QC	-	4.1	4.6	28.9	19.7	57.3
ON	7.3	-	-	18.9	-	26.3
AT	9.2	-	-	-	9.2	18.4
NY	10.5	1.7	-	-	1.9	14.1
NE	17	-	3.2	5.5	-	25.7
Total	44.0	5.8	7.8	53.3	30.8	141.7

(b) Optimal transmission

TABLE 1.3 – Transmission flow in TWh between sub-regions, before losses (from sub-region in row, to sub-region in column).

Figure 1.1 illustrating the trends in Quebec's energy imports and exports over the year highlights that Quebec exports mostly during summer and winter when demand in the region is high, while it imports mostly in spring and fall to absorb solar and wind generation surplus.



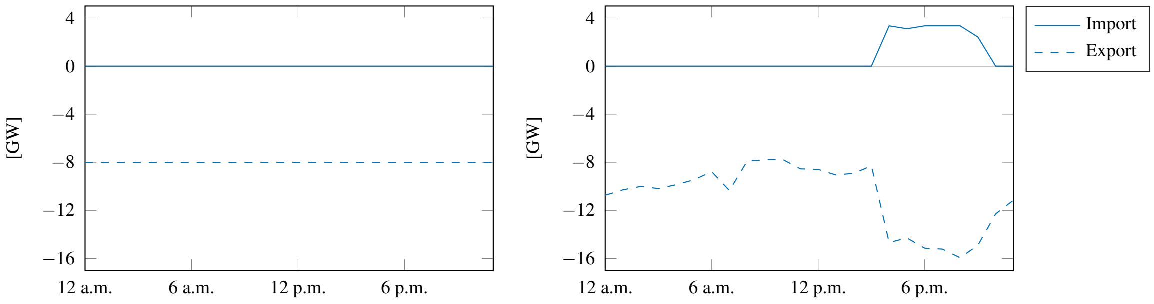
(a) Constrained transmission

(b) Optimal transmission

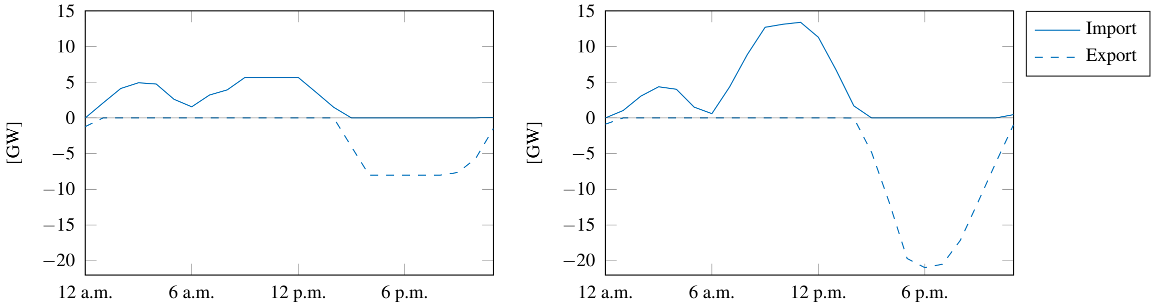
FIGURE 1.1 – Weekly average of energy imports (positive) and exports (negative), in GWh, in Quebec over a year.

When comparing Figures 1.1.a and 1.1.b, we notice that in both scenarios, energy trades follow the same time pattern. However, the import and export levels are higher in the optimal transmission scenario. The pattern of imports and exports from Quebec over the year suggests that energy trade with Quebec can provide a seasonal balancing service to neighbouring jurisdictions.

Figure 1.2, shows the within-day electricity imports and exports in Quebec at winter and summer peaks.In Figures 1.2.a and 1.2.b we observe that in the winter peak, under the constrained transmission scenario, Quebec exports remain constant throughout the day, at around 8 GW per hour, which corresponds to its maximum capacity, whereas there are no imports along the day. In the optimal transmission scenario, Quebec exports from about 8 GW to nearly 16 GW throughout the day. Exports are more important at the end of the day when Quebec also imports close to 4 GW.



(a) Winter peak - Constrained transmission (b) Winter peak - Optimal transmission



(c) Summer peak - Constrained transmission (d) Summer peak - Optimal transmission

FIGURE 1.2 – Imports and exports in Quebec per hour in GW on winter and summer peak.

When observing figures 1.2.c and 1.2.d, we first notice that in both scenarios, at summer peak, Quebec imports in the morning and midday and then exports at the end of the day. This corresponds to the cooling and demand peak, as well as the decrease in solar generation. In both scenarios, the exchanges follow the same pattern over the day. However, the imports and exports of Quebec are more important in the optimal transmission scenario.

The hourly patterns of Quebec imports and exports, in the summer peak, in the optimal transmission scenario reveal that Quebec imports during the daytime to absorb excess generation from solar in other sub-regions. Similarly, Quebec exports during the evening peak hours, when solar production is much lower. Access to Quebec hydropower therefore seems to offer a daily balancing service and even more : Quebec can keep water in its reservoirs and import during low-demand seasons, allowing for monthly, long term balancing. This energy is used and re-exported much later, something that could not be done with short-term storage.

1.3.3 Energy balance

Table 1.4, presents the energy balance for each sub-region for both scenarios. In particular, we find that in the constrained transmission scenario, the Atlantic provinces, New York and New England use energy storage, while in the optimal transmission scenario, only New York and New England use storage, and, the amount of energy stored decreases by 48% for the entire region. Furthermore, renewable gas use throughout the region drops by 35% from the constrained to the optimal transmission scenario, with decreases between 27% and 48% in Ontario, the Atlantic provinces, New York and New England. Additionally, we find that wind generation in the region increases despite lower additional capacity installed. This results partly from a reduction in curtailment from 11% in the constrained scenario to 6% in the optimal scenario.

	QC	ON	AT	NY	NE	Total
Load	201.42	164.92	42.45	241.16	185.68	835.64
Demand response	1.11	8.09	2.25	16.11	12.09	39.66
Load shedding	-	-	-	-	0.01	0.01
Storage	-	-	-0.27	-2.41	-0.74	-3.43
Solar	-	6.42	-	40.25	22.60	69.27
Wind	9.10	29.85	37.67	66.29	103.30	246.21
Wind curtailment	0%	9%	15%	7%	14%	11%
Renewable gas	-	0.38	1.12	10.47	8.82	20.80
Hydro	202.90	34.77	4.22	29.08	5.85	276.82
Nuclear	-	110.33	5.76	44.72	32.92	193.73
Import	20.36	13.80	8.35	50.93	27.36	120.81
Export	32.05	38.73	16.64	14.28	26.55	128.25

(a) Constrained transmission

	QC	ON	AT	NY	NE	Total
Load	201.42	164.92	42.45	241.16	185.68	835.64
Demand response	7.00	6.23	1.83	14.37	10.25	39.68
Load shedding	-	-	-	0.00[1]	0.02	0.02
Storage	-	-	-	-0.97	-0.79	-1.77
Solar	-	5.09	0.66	41.26	21.57	68.58
Wind	9.08	26.66	40.25	68.03	106.57	250.60
Wind curtailment	0%	4%	8%	4%	7%	6%
Renewable gas	0.04	0.28	0.58	7.41	5.28	13.59
Hydro	201.23	34.78	4.22	29.11	5.85	275.19
Nuclear	-	112.69	5.89	45.74	33.65	197.98
Import	41.41	5.45	7.39	50.25	29.02	133.52
Export	57.34	26.26	18.36	14.04	25.75	141.74

(b) Optimal transmission

[1] 7.63 MWh of load shedding in New York

TABLE 1.4 – Energy balance in TWh per sub-region and scenario.

We further observe that from the constrained to the optimal transmission case, the use of demand response in Quebec rises from about 1.1 TWh to nearly 7 TWh. This allows Quebec to increase its exports. More specifically, Quebec relies heavily on demand response when its exports are important.

Finally, we notice that load shedding increases by 36% throughout the region. It is mainly used in New England and somewhat in New York. For instance, in the optimal transmission scenario, New England relies on load shedding 6 times over the year, for a total of almost 20 GWh, even though its combined wind and solar installed capacity is close to 54 GW which is slightly over twice its peak demand. In the constrained scenario, New England used load shedding on 7 occasions for a total of more than 10 GWh. The additional transmission therefore reduces the incidence of load shedding even though the magnitude of the events increases. The level of load shedding increases because there is less additional capacity installed in New England, in particular renewable natural gas, in the optimal transmission scenario than in the constrained transmission scenario. This load shedding occurs during winter peak hours when wind generation is very low due to lack of wind. This is an extreme situation that demonstrates that with a strong penetration of renewable energy, their intermittency and dependence on weather present a significant risk.

Thus, increasing transmission capacity between sub-regions not only reduces the use of renewable gas and storage requirements, but also allows for greater penetration of wind generation, in particular by facilitating surplus wind generation exports, thereby reducing wind curtailment.

1.3.4 Costs distribution and regional impact

In the constrained transmission scenario, achieving 100% decarbonization would cost the region about $40 billion a year, whereas under the optimal transmission scenario, it would cost $36.7 billion a year. This represents a systemwide annual cost avoidance of 9%. However, this savings for the system do not necessarily mean that the costs and benefits are evenly allocated among the sub-regions. This is why we now investigate the breakdown of this distribution.

First, we analyze the impact of relaxing the transmission investment constraint on the average hourly short-run marginal cost (SRMC) of electricity in each sub-region, which can be interpreted as the hourly price of electricity, as illustrated in Figure 1.3. We can see that increased transmission capacity with Quebec leads to a decrease in the average SRMC in Ontario, the Atlantic provinces, New York and New England of between 4% and 7% and an increase in QC (i.e. a convergence of costs across regions). We also observe in Table 1.5, which presents key statistics on SRMC, that SRMC is less volatile with new transmission particularly in New York, New England and the Atlantic provinces. Also in these sub-regions, the minimum SRMC tends to be greater. This results from a greater ease of exporting surplus generation, which leads to more stable prices.

On the opposite, in Quebec, we observe that the average SRMC increases with increased transmission capacity, and so does its volatility. Indeed, the growth in trade leads to converging regional SRMC, transferring some of the other regions' volatility to Quebec.

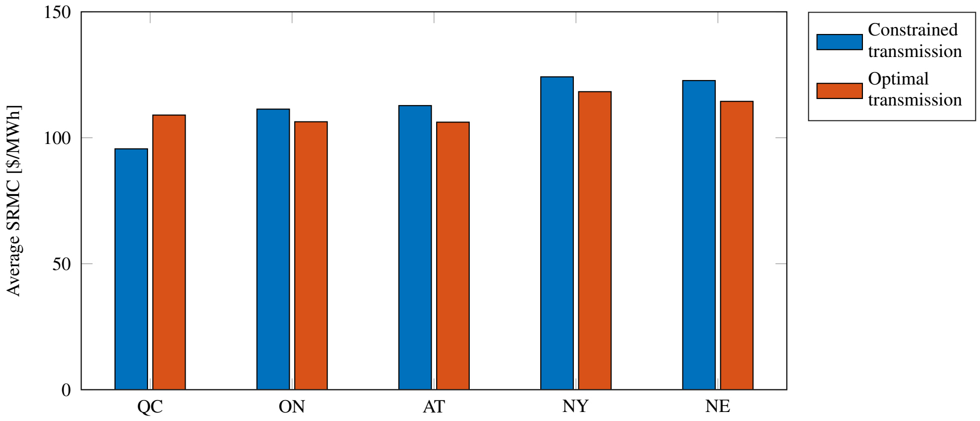


FIGURE 1.3 – Average hourly short-run marginal cost (SRMC) of electricity in $/MWh per sub-region and scenario.

	QC	ON	AT	NY	NE
Min	6	2	3	2	2
Mean	96	111	113	124	123
Max	200	8,874	9,420	9,420	10,000
SD	15	163	291	287	308

(a) Constrained transmission

	QC	ON	AT	NY	NE
Min	3	2	3	2	3
Mean	109	106	106	118	114
Max	9,420	8,874	9,420	10,000	10,000
SD	244	173	257	261	273

(b) Optimal transmission

TABLE 1.5 – Statistics on the hourly short-run marginal cost (SRMC) of electricity in $/MWh per sub-region and scenario.

As the optimal solution to the model relies on the assumption of perfect competition, SRMC is the variable of most immediate concern to consumers as the wholesale price of energy equal the SRMC. Therefore, it may be difficult to gain social acceptability in Quebec for expanding trade with neighbouring jurisdictions. It could lead to higher prices, as long as there is some pass-through of marginal costs to consumers.

For each sub-region, we then investigate the change in trade balance and its components (export revenues and import costs), the change in total costs, and finally the change in regional surplus, defined as the change in consumer and producer surplus, from the constrained to the optimal transmission scenario. The costs under consideration here are investment costs (due to the generation capacity expansion), operation and maintenance costs and new transmission line costs. The costs of a new transmission line are allocated equally between the two sub-regions linked by this line. Therefore, the surplus is defined as the difference between trade balance and total costs, everything else being within-region redistribution, which depends on the market structure and political economy of pricing schemes and is thus not determined within the model. Percentage changes (absolute changes are in parentheses) in these elements for each sub-region and for the region are presented in Table 1.6 below. We can only compute the change in surplus, but not the initial surplus, as we cannot know the actual consumer surplus, without knowing the demand function. We cannot therefore compute the relative change (in %) in the surplus. We can, however, compute the relative changes in the other components of the surplus (trade balance and costs), since for these we can find the initial value.

	QC	ON	AT	NY	NE	Region
Export revenues	63% (4.0)	-46% (-3.1)	-22% (-0.5)	-55% (-0.9)	-32% (-0.7)	-6% (-1.2)
Import costs	25% (0.5)	-67% (-1.4)	-8% (-0.1)	-3% (-0.3)	1% (0.1)	-6% (-1.2)
Trade balance	79% (3.6)	-36% (-1.7)	-33% (-0.4)	-9% (-0.7)	-24% (-0.8)	- (0.0)
Investment costs	- (0.04)	-36% (-0.5)	-3% (-0.1)	-5% (-0.5)	-4% (-0.5)	-6% (-1.5)
Operation costs	123% (0.8)	-13% (-0.3)	-23% (-0.2)	-20% (-1.2)	-24% (-1.3)	-14% (-2.2)
Transmission costs	- (0.5)	-45% (-0.1)	8% (0.01)	-20% (-0.1)	-11% (-0.03)	21% (0.2)
Total costs	197% (1.3)	-23% (-1.0)	-8% (-0.3)	-11% (-1.8)	-11% (-1.8)	-9% (-3.4)
Regional Surplus	(2.2)	(-0.7)	(-0.2)	(1.1)	(1.0)	(3.4)

TABLE 1.6 – Cost and revenue changes in % and $G (in parentheses) from the constrained to the optimal transmission scenario for each sub-region.

Quebec's trade balance increases by 79% with the addition of transmission capacity. This increase is explained by trade with Quebec being used for balancing purposes. Thus, Quebec imports during periods of surplus production, i.e., when prices are low, and exports when demand is high and supply limited, i.e., when prices are high.

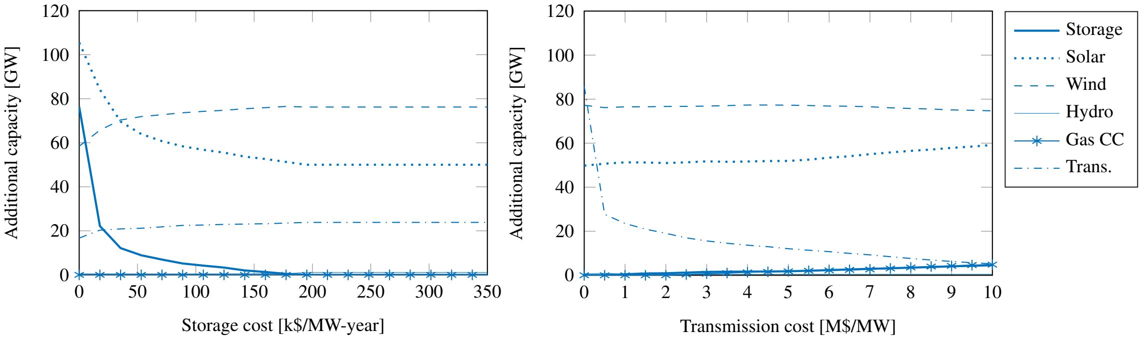
Total costs in Quebec almost triple from about \$0.7 billion to over \$2 billion with most of the increase due to higher operating and transmission costs, while in all other sub-regions total costs decrease by 8% to 23%. Costs for new transmission lines across the region increase by about 21%, from over \$1.1 billion in the constrained scenario to over \$1.3 billion in the optimal case. However, Ontario, New York and New England see their transmission costs decrease by about 45%, 20% and 11% respectively. This is a result of the reduced additional transmission capacity installed with these three sub-regions from the constrained to the optimal transmission scenario. In contrast, in Quebec the costs of new transmission lines increase from \$0 in the constrained scenario to slightly more than \$460 million in the optimal scenario. Also, in the Atlantic provinces, new transmission line costs increase by \$12 million from the constrained to the optimal scenario.

Finally, the surplus in Quebec, New York and New England increase by \$2.2 billion, \$1.1 billion and \$1 billion respectively. On the opposite, Ontario and the Atlantic provinces experience a \$0.7 billion and \$0.2 billion decrease in surplus respectively. Therefore, this highlights that the costs and benefits are not evenly allocated between sub-regions, as some experience gains in surplus while others experience losses in surplus. Allowing for the optimal addition of new transmission seems to benefit Quebec, which experiences a significant increase in its trade balance by exporting when electricity prices are high and importing when prices are lower. New York and New England also benefit from the optimal addition of transmission lines. Indeed, additional transmission lines with Quebec allow them to lower their investment requirements in generation and storage capacity as well as in transmission capacity. Ontario and Atlantic provinces are experiencing surplus losses primarily because their trade balances decrease more strongly than their costs due to significant reductions in export revenues.

1.3.5 Sensitivity to transmission and storage costs

In Figure 1.4 we can compare the installed storage capacity with the additional solar, wind and transmission capacity installed as a function of storage investment cost (1.4.a) and as a function of transmission investment cost (1.4.b) for the entire region under the optimal transmission scenario. Operation costs remain unchanged. Figure 1.4.a is generated by re-solving for the optimal solution for each value of storage investment cost while keeping transmission cost at its initial value (\$1M/MW). In a similar way Figure 1.4.b is generated by re-solving for the optimal solution for each value of transmission cost while keeping storage investment cost at its initial value (\$177k/MW-year). Thus, for each of the generation technologies, the curves obtained are similar to demand functions which relate the marginal value of each technology as a function of storage or transmission costs.

In Figure 1.4.a we observe that installed storage capacity decreases with its cost and there is no additional storage installed when its annualized investment cost is above \$190,000/MW-year. Likewise, additional solar capacity falls from about 106 GW when the storage cost is zero to 50 GW when it exceeds \$190,000/MW-year. As solar and storage capacities both increase as the cost of storage decreases, this suggests that storage and solar are two complementary technologies. Furthermore, as the cost of storage increases, the additional wind capacity and transmission capacity installed both increase, suggesting that wind and transmission are complements. Also, there is no additional gas capacity installed, regardless of the price of storage.



(a) As a function of storage cost.

(b) As a function of transmission cost.

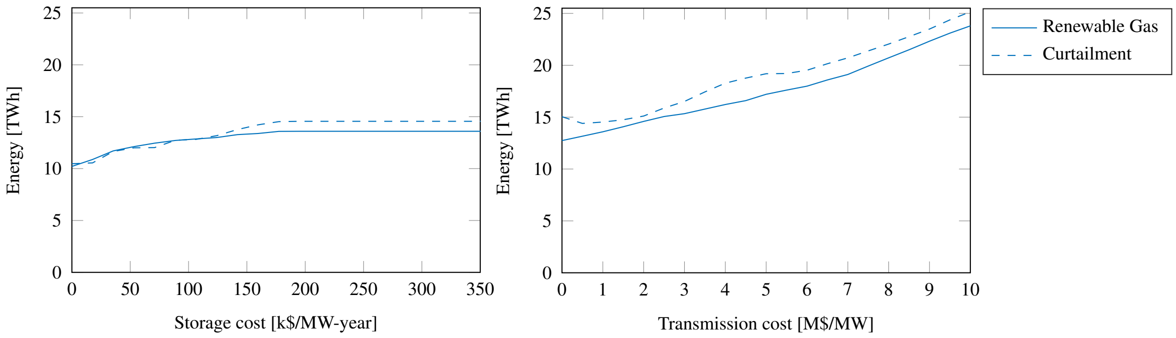
FIGURE 1.4 – Additional capacity per technology in GW under the optimal transmission scenario.

In Figure 1.4.b, we notice that the installed wind capacity is mostly independent of the the cost of transmission, from about 76 GW to slightly under 75GW when the transmission cost reaches \$10M/MW. This results primarily from the decrease in transmission capacity that limits the ability to export wind generation surplus, as well as the increase in installed renewable gas capacity.We also observe that additional transmission capacity decreases as its investment cost increases, from

80 GW when it is free to slightly over 5 GW when its cost reaches over \$10M/MW. As transmission costs increase, and consequently additional transmission capacity decreases, sub-regions cannot take as much advantage of trades to meet their power and energy requirements and therefore must rely on other technologies, which is why the additional capacities of solar, storage, and renewable gas installed slightly increase with the cost of transmission. Nevertheless, when transmission costs hit \$10M/MW, 96% of the new transmission capacity installed in the region is between Quebec and the other four sub-regions, compared to 69% when transmission is at its reference cost. The region thus appears to prioritize transmission lines with Quebec as the cost increases. This suggests that even when transmission is very expensive, access to Quebec reservoirs still remains valuable.

We also find that when transmission cost is zero, there is no additional storage capacity installed whereas when storage cost is zero, over 16 GW of transmission capacity is installed. This shows us that transmission can obviate the need to install additional storage if the cost of transmission is low enough, but not the other way around. Hence, transmission lines are valuable even when storage is free.

As illustrated in Figure 1.5, renewable gas generation and curtailment increase with storage cost and with transmission cost. In Figure 1.5.a, we see that generation and curtailment stop increasing when the cost of storage exceeds \$190k/MW-year, which is the threshold where there is no more storage installed. The increase in renewable gas generation and curtailment is not surprising given that installed wind capacity increases with storage cost whereas storage capacity decreases.



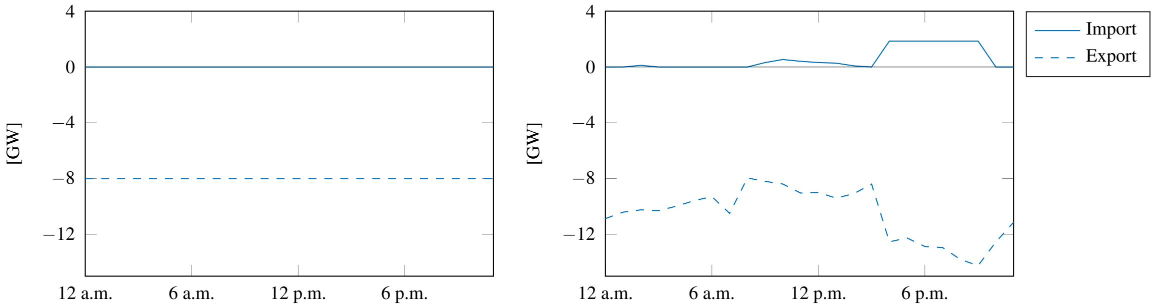
(a) As a function of storage cost.

(b) As a function of transmission cost.

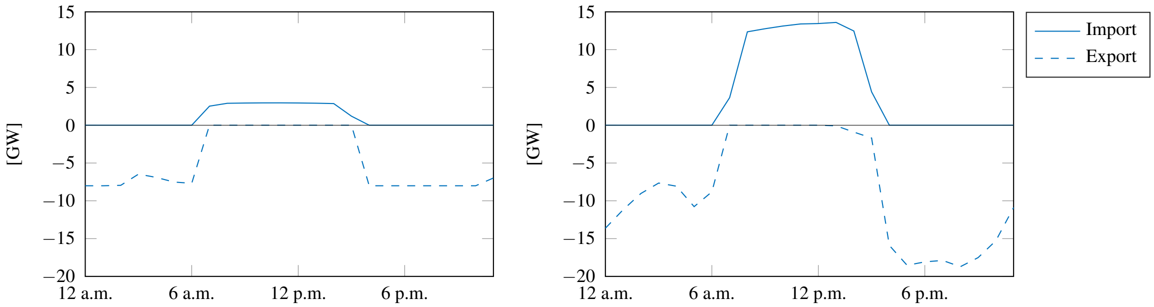
FIGURE 1.5 – Generation from renewable gas in TWh and variable generation curtailment throughout the region under both scenario, as a function of storage investment cost in k\$/MW.

In Figure 1.5.b, curtailment and renewable gas generation increase when the transmission cost increases. Also, we have noted in Figure 1.4.b that as the cost of transmission lines increases, the new transmission capacity installed decreases whereas new wind capacity installed remains unchanged. This suggests that none of the available technologies can overcome the increase in renewable gas generation and curtailment occurring as transmission capacity decreases. This shows, once again, that additional transmission allows for better balancing of wind generation and that storage is not a substitute for transmission.

The import and export of electricity in Quebec on two representative days of the year under both scenarios, when storage is free, is presented in Figure 1.6 below. Figures 1.6.a and 1.6.b show that at the winter peak, in the constrained transmission scenario, Quebec exports at its full capacity every hour of the day, i.e. 8 GW, while there are no imports. In the optimal transmission scenario, Quebec exports during the day vary from about 8 GW to slightly above 14 GW each hour and are higher at the latter hours of the day, precisely when Quebec begins to import about 2 GW.



(a) Winter peak - Constrained transmission (b) Winter peak - Optimal transmission



(c) Summer peak - Constrained transmission (d) Summer peak - Optimal transmission

FIGURE 1.6 – Imports and exports in Quebec per hour in GW on winter and summer peak, when storage is free.

Comparing figures 1.6.c and 1.6.d, we first see that in the constrained transmission scenario, Quebec exports, at around its maximum capacity, 8 GW, at night. Exports cease from about 8 :00 a.m. to 3 :00 p.m., while Quebec begins to import about 3 GW. In the optimal transmission scenario, Quebec exports mostly at night and in the evening (between 3 :00 p.m. and 9 :00 p.m.), with between 8 GW and over 18 GW exported per hour. Once again, exports will cease during the day, while Quebec imports up to 14 GW.

The hourly patterns of imports and exports in Quebec, in the optimal transmission scenario, reveal that Quebec imports to absorb solar generation excess from other sub-regions during the day in summer, and wind generation excess during the night in winter. Similarly, it exports during the morning and the end-of-day consumption peaks, in both winter and summer, when solar generation is lower. Energy trade with Quebec therefore seems to provide a daily balancing service, even when short-duration storage is free.

Figure 1.7 compares this “reference cost" distribution of change in surplus to a scenario in which storage is completely free. The figure shows that the NPCC’s region’s surplus gain from transmission is 21% lower if storage is free, but remains substantial at 2.7$ billion.

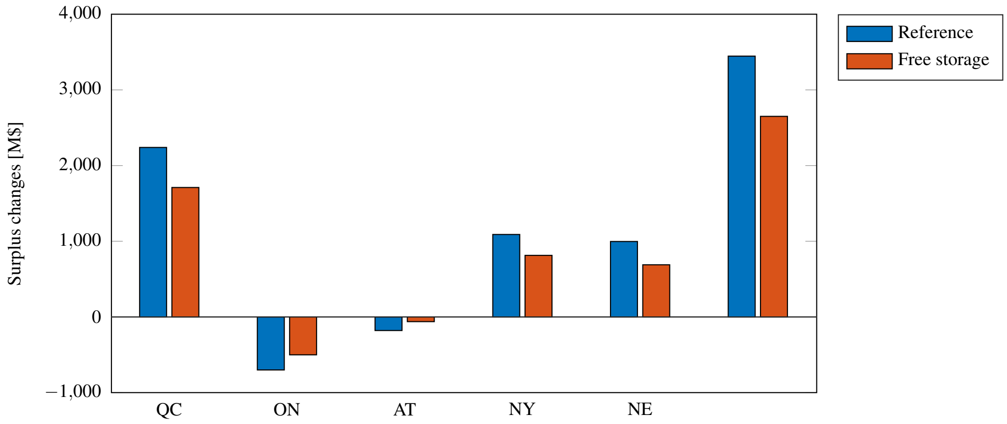


FIGURE 1.7 – Surplus changes in $M from the constrained to the optimal transmission scenario for each sub-region.

Ontario and the Atlantic provinces have higher surplus gains when storage is free, but still remain negative. In contrast, Quebec, New York and New England experience lower surplus gains by 24%, 25% and 31% respectively. In Quebec, this results from a lower growth in the trade balance and a higher increase in costs, while in New York and New England it results from a higher decrease in the trade balance. As the (uneven) allocation of costs and benefits is left mostly unchanged by its availability, we conclude that short-term storage cost has no significant influence on the allocation of costs and benefits across the sub-regions.

1.4 Conclusions and Policy Implications

Like many other regions, decarbonizing Northeastern North America will require significant changes for their power systems. This implies installing significant amounts of solar and wind power. Storage and flexible resources become therefore critical considering the intermittency of renewable generation resources. Several studies on the Northeast have documented the impact of decarbonization on generation and storage capacity requirements, as well as the benefits of regional integration. Most, however, overlook the ability of existing reservoirs combined with new transmission capacity to reduce the need for new generation capacity and additional storage.

Our findings highlight the economic benefits of accessing existing hydro reservoirs in Quebec to decarbonize the Northeast, as well as the relationship between the competing technologies. However, they also highlight that decarbonization will require a significant reform of the power system and energy market.

To decarbonize the Northeast, jurisdictions should expect to make significant investments. Almost doubling installed generation capacity is required to meet new and higher demand using carbon-free generation. Increased transmission capacity between regions, especially access to Quebec reservoirs, can not only reduce decarbonization costs, but also reduce the generation capacity to be installed. By allowing access to Quebec reservoirs, the region can avoid installing 8 GW of new generation capacity and reduce by \$3.4 billion total decarbonization costs. This is true even if the cost of short-term storage technologies was to significantly drop.

While the economic impacts are quite significant, the social implications are not to be ignored. Indeed, a major challenge lies in the political difficulty of developing new transmission lines as transmission projects often have a poor social acceptability. Also, with the growing need for solar and wind power, it is likely that opposition to the development of large-scale solar and wind farms will increase. Thus, a trade-off between economic benefits and opposition to transmission lines and new solar and wind facilities will have to occur. This paper helps validate the robustness of these economic benefits.

Furthermore, as the economic impact is highly variable between and even within subregions, there are many barriers to greater collaboration. For instance, for consumers and producers, changes in prices can be perceived as a burden, and therefore they might oppose the expansion of transmission capacity. Moreover, despite the fact that Quebec is the region with the largest surplus gain, New York and New England are among those that benefit the most from integrating Quebec's reservoirs. Specifically, New York and New England reduce their total costs while increasing generation from renewable energy. These sub-regions might need to share some of these benefits with other sub-regions to get them to agree to install new transmission lines. Implementing appropriate redistribution mechanisms is therefore crucial to enable greater cooperation between subregions.

Finally, our study also highlights the complementary relationship between short-term storage and solar, as more storage at a lower cost allows more solar to be installed. Similarly, wind and transmission appear to be complementary as additional transmission supports wind integration, especially by reducing curtailment. In contrast, it shows that additional transmission reduces the need for short-term storage, but not the other way around. Access to Quebec reservoirs also reduces the renewable gas generation requirements.

This paper contributes to the understanding of benefits from existing reservoirs and new interconnection capacity in decarbonizing the Northeast. Further research should explore the sensitivity of the value of hydro reservoirs to the uncertainty brought by weather dependent variables such as water inflows.

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A. Supplementary Data

Load :

Reference load correspond to 2018 load profiles used by Rodríguez-Sarasty et al. (2021).

	QC	ON	AT	NY	NE	Region
Reference load (2018)						
Peak (MW)	36,144	23,240	7,885	31,861	25,568	108,870
Peak date	Jan, 6th	Sept, 5th	Jan, 3rd	Aug, 29th	Aug, 29th	Jan, 6th
Total energy (TWh)	183	137	39	161	123	644
New load profile						
Peak (MW)	39,759	27,888	8,673	53,923	43,816	169,327
Peak date	Jan, 6th	Sept, 5th	Jan, 3rd	Jan, 6th	Jan, 2nd	Jan, 5th
Total energy (TWh)	201	165	42	241	186	836

TABLE A.1 – Details of hourly loads

Investment and operation costs :

Annualized investment costs are calculated using a 6% discount rate. For natural gas, the fuel cost is based on a natural gas price of \$3/MBtu. For CCGT, the heat rate is 7,627 Btu/kWh and 11,138 Btu/kWh for CT.

	Lifespan [year]	Investment cost [k\$/MW]	Annualized Investment cost [k\$/MW-yr]	Fixed O&M cost [k\$/MW]	Variable O&M cost [\$/MWh]	Fuel cost [\$/MWh]
CCGT	25	926	68.34	13.33	3.00	22.00
CT	25	919	67.82	19.37	7.00	33.00
Hydro	75	8,000	458.63	14.85	2.46	-
Nuclear	40	6,742	422.72	101.00	2.00	7.00
Solar	25	1,111	81.99	20.00	-	-
Storage[1]	10	1,384	177.40	37.11	-	-

[1] A 81% efficiency rate is assumed

TABLE A.2 – Investment and operation costs per technology.

Carbon-neutral gas parameters :

	Capacity [TWh]	Cost factor[1]
Block 1	50	× 5
Block 2	250	× 25

[1] Applied to fuel costs of conventional technology

TABLE A.3 – Carbon-neutral natural gas capacity and cost factor.

Wind parameters :

		QC	ON	AT	NY	NE
Capacity [GW]	W1	0	5	5	5	5
	W2	0	5	10	5	5
	W3	0	50	50	40	40
Investment cost [k$/MW]	W1	1,200	1,202	1,201	1,203	1,204
	W2	1,623	1,625	1,624	1,626	1,627
	W3	2,999	3,001	3,000	3,002	3,003
Fixed O&M cost [k$/MW]	W1	44				
	W2					
	W3					

TABLE A.4 – Wind capacity potential and costs per technology and sub-region.

Demand response and load shedding parameters :

Three block of demand response are available with an increasing price. Given the complexity of estimating precisely the cost of demand response programs, we use these values as representative values of possible voluntary load reduction programs (such as accepting a colder or warmer temperature for one hour). These values represent the compensation received by consumers for reducing their load by 5%. These demand response actions are not load shifting actions. Load shedding by the system is also possible at much higher cost ($10,000/MWh). Table A.5 below presents the capacity and unitary costs of each block of demand response.

	Capacity [% of load]	Cost [$/MWh]
DR1	5%	100.00
DR2	5%	150.00
DR3	5%	200.00

TABLE A.5 – Demand response capacity and costs.

Conclusion générale

Comme pour beaucoup d'autres régions, la décarbonation du nord-est de l'Amérique du Nord nécessitera des changements importants pour les réseaux électriques. En effet, cela implique l'installation de quantités importantes d'énergie solaire et éolienne. Le stockage et les ressources flexibles deviennent donc essentiels compte tenu de l'intermittence des ressources de production renouvelables. Plusieurs études sur le Nord-Est ont documenté l'impact de la décarbonation sur les besoins en capacité de production et de stockage, ainsi que les avantages de l'intégration régionale. Cependant, la plupart d'entre elles négligent la capacité des réservoirs existants, combinés à de nouvelles lignes de transmission, à réduire le besoin en nouvelles capacités de production et de stockage supplémentaire.

Les résultats de la présente étude soulignent les avantages économiques de l'accès aux réservoirs hydroélectriques existants au Québec pour décarboner le Nord-Est, ainsi que la relation entre les technologies concurrentes. Cependant, ils mettent également en évidence que la décarbonation nécessitera une réforme profonde du secteur électrique et du marché de l'énergie.

Pour décarboner le Nord-Est, les juridictions doivent s'attendre à faire des investissements importants. Il faut presque doubler la capacité de production installée pour répondre à une demande nouvelle et plus élevée à partir de sources de production carboneutre. L'augmentation de la capacité de transmission entre les régions, notamment l'accès aux réservoirs du Québec, peut non seulement réduire les coûts de décarbonation, mais aussi la capacité de production à installer. En permettant l'accès aux réservoirs du Québec, la région peut ainsi éviter l'installation de 8 GW de nouvelle capacité de production et réduire de 3,4 milliards de dollars les coûts totaux de décarbonation. Ceci est vrai même si le coût des technologies de stockage court terme devait baisser de manière significative.

Si les impacts économiques sont importants, les implications sociales ne sont pas pour autant à négliger. En effet, un défi majeur réside dans la complexité politique du développement de nouvelles lignes de transmission, étant donné que les projets de transmission présentent souvent une faible acceptabilité sociale. De plus, avec la demande croissante pour les énergies solaire et éolienne, il est probable que l'opposition au développement de parcs solaires et éoliens à grande échelle augmente. Il faudra donc trouver un compromis entre les avantages économiques et l'opposition aux lignes de transport et aux nouvelles installations solaires et éoliennes. Ce mémoire permet de valider la robustesse de ces avantages économiques.

De surcroît, il est crucial d'assurer une répartition équitable des coûts et des bénéfices entre les juridictions. L'impact économique étant très variable d'une sous-région à l'autre et même au sein d'une même sous-région, les obstacles à une plus grande collaboration pourraient être nombreux. Par exemple, pour les consommateurs et les producteurs, les changements de prix peuvent être perçus négativement, et ils pourraient donc s'opposer à l'expansion de la capacité de transmission. De plus, malgré le fait que le Québec soit la région qui connaît le plus grand gain de surplus, New York et la Nouvelle-Angleterre sont parmi les régions qui profitent le plus de l'intégration des réservoirs du Québec. Plus précisément, New York et la Nouvelle-Angleterre bénéficient d'une diminution de leurs coûts totaux tout en augmentant leur production à partir d'énergie renouvelable. Ces juridictions pourraient avoir besoin de partager certains de ces bénéfices avec d'autres juridictions pour qu'elles acceptent le développement de nouvelles lignes de transmission. La mise en œuvre de mécanismes de redistribution appropriés est donc cruciale pour permettre une plus grande coopération entre les juridictions.

Enfin, ce travail met également en évidence la complémentarité entre le stockage court terme et le solaire, puisque davantage de stockage à un coût moindre permet d'installer davantage de solaire. De même, l'éolien et la transmission semblent être complémentaires, étant donné que davantage de transmission favorise l'intégration de l'éolien, notamment en réduisant le plafonnement. En revanche, la transmission supplémentaire réduit le besoin en stockage court terme, mais pas l'inverse. L'accès aux réservoirs du Québec réduit également les besoins de production à partir du gaz renouvelable.

Ce mémoire contribue donc à la compréhension des avantages que présentent les réservoirs existants et la nouvelle capacité d'interconnexion pour décarboner le Nord-Est. D'autres recherches pourraient explorer la sensibilité de la valeur des réservoirs hydroélectriques à l'incertitude apportée par les variables dépendantes des conditions météorologiques telles que les apports hydriques.

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