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Infrastructures dans le Nord du Canada : Développement routier et décarbonisation

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Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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Cette thèse intitulée:

Infrastructures dans le Nord du Canada : Développement routier et décarbonisation

présentée par **Thomas STRINGER**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*

a été dûment acceptée par le jury d'examen constitué de :

Mario BOURGAULT, président
Marcelin JOANIS, membre et directeur de recherche
Ari VAN ASSCHE, membre
Simon LANGLOIS-BERTRAND, membre externe

DÉDICACE

« Par nature tout ce qui est foi monte; et tout ce qui monte converge inévitablement. »

Pierre Teilhard de Chardin (1881-1955).

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RÉSUMÉ

La qualité de vie des habitants du Nord canadien dépend des infrastructures qui relient ces collectivités éloignées au Sud du pays et de celles qui permettent à ces communautés de réduire leurs coûts de transport et d'énergie. Construire ces infrastructures engendre de projets massifs qui doivent être entrepris avec prudence, qu'il s'agisse de nouvelles routes, de lignes électriques ou de centrales électriques. En effet, les coûts associés à de tels projets sont immenses et leurs effets à long terme ne sont pas bien connus dans le contexte nordique. Néanmoins, une meilleure compréhension de ce que ces infrastructures généreront sur le plan socio-économique ou de leur coût peut aider les parties prenantes gouvernementales à mieux comprendre ce que les populations nordiques peuvent en retirer.

Les propositions de développement des infrastructures dans le Nord du Canada gagnent du terrain sur le plan politique, notamment celle d’un corridor reliant les régions du nord de chacune des provinces du pays. Le Québec est la province la plus grande et la plus septentrionale du Canada et jouerait un rôle central dans la construction du corridor. L'analyse des phases historiques du développement du Nord québécois est crucial pour évaluer les défis à venir. La première section de cette thèse regroupe les développements des infrastructures du Québec en trois phases principales, synthétise chaque phase et les compare de manière critique au concept de Corridor nordique canadien. Aucune recherche n'a encore examiné la complémentarité du corridor avec l'historique du développement des infrastructures nordiques au Québec. Alors que les phases précédentes pouvaient être catégorisées comme des corridors de pénétration intraprovinciale reliant le nord au sud du Québec, le corridor nordique vise à développer un corridor économique interprovincial pour les provinces enclavées afin d'avoir un meilleur accès maritime. Parmi les obstacles découlant de la conciliation des développements passés avec le corridor nordique figurent l'inadéquation de l'utilisation des infrastructures existantes au Québec pour un corridor pancanadien et des trajectoires de développement différentes aux niveaux provincial et fédéral. Trois options de tracé pour le corridor nordique au Québec sont présentées dans cette étude. Plus généralement, cet article décrit les difficultés propres au développement de corridors éloignés subarctiques.

Comme infrastructure essentielle de transport, la connexion routière est considérée comme un moteur important du développement économique. Cependant, pour les communautés subarctiques

éloignées, cela peut également signifier un énorme changement dans leur mode de vie. Quelle est l'ampleur des avantages socio-économiques de la connexion routière ? La deuxième section de cette thèse utilise des données de recensement du Nord du Québec et du Labrador pour évaluer les effets du raccordement routier sur les municipalités raccordées entre 1986 et 2016. À l'aide d'un modèle de régression, assorti de vérifications de robustesse, nous constatons que le raccordement routier est corrélé avec une augmentation des taux d'emploi et du niveau d'instruction et une diminution du chômage. Bien que nous trouvions également des corrélations positives et significatives entre la connexion routière et le revenu dans de nombreuses spécifications, ce résultat particulier n'est pas statistiquement robuste. Dans l'ensemble, nos résultats appuient la conjecture selon laquelle le raccordement routier des municipalités éloignées génère des avantages économiques non négligeables.

À l’échelle du Canada, la transition des sources d'énergie non renouvelables vers les sources d'énergie renouvelables est un thème important de la politique énergétique du gouvernement fédéral. Cependant, les investissements requis pour une telle transition sont souvent considérés comme étant assez coûteux. Au Canada, des recherches antérieures ont montré qu'une transition est économiquement plausible au niveau national. Cependant, une transition énergétique est-elle tout aussi plausible pour chacune des provinces du Canada? La troisième section de cette thèse utilise des données de simulation d'utilisation d'énergie et un modèle de coût pour évaluer les dépenses d'infrastructure pour une transition net-zéro pour chacune des dix provinces du pays d'ici 2060. En calculant les coûts pour cinq scénarios différents et en tenant compte les économies engendrées par la baisse de la consommation de combustibles fossiles après la transition, nous constatons que la plupart des provinces du Canada ont tout à gagner d'une transition énergétique pancanadienne en captant chacune des économies de combustibles fossiles. Nous constatons également qu'en général, les provinces qui produisent de l'électricité à partir de combustibles fossiles devraient bénéficier de plus d'économies après une transition que les provinces qui produisent actuellement de l'électricité à partir de sources renouvelables.

Le Canada produit la majeure partie de son électricité à partir d'énergies renouvelables. Cependant, dans les communautés éloignées qui ne sont pas connectées au réseau principal du sud du Canada, la quasi-totalité des micro-réseaux dépendent des combustibles fossiles pour assurer l'approvisionnement en électricité. Combien coûterait la décarbonisation de tous ces micro-réseaux ? La quatrième partie de cette thèse utilise une approche basée sur les coûts couplée à un

modèle d'optimisation pour trouver la solution de décarbonisation la moins coûteuse pour chaque communauté éloignée d'ici 2050. En utilisant les données de vitesse du vent et d'irradiance solaire, de même que des données sur la production future et des estimations des coûts de stockage, notre modèle détermine si l'énergie solaire ou éolienne est plus appropriée pour une communauté et à quelle période il est préférable de passer de la production de combustibles fossiles aux énergies renouvelables. Nos résultats montrent que le coût de la décarbonisation des micro-réseaux éloignés du Canada n'est pas prohibitif et quelle technologie et quelle période de mise en œuvre sont les moins chères pour chaque communauté. Nous constatons qu'en 2020, les éoliennes seraient l'option la moins chère pour la plupart des communautés, alors qu'en 2050, les panneaux solaires seraient l'option la moins chère pour la plupart des communautés. Celles qui utilisent actuellement du diesel ou du fioul lourd pour produire de l'électricité devraient envisager de se décarboniser dès que possible, tandis que celles qui utilisent du gaz naturel pourraient attendre que les technologies de production et de stockage deviennent moins chères. Les plus grandes agglomérations et les communautés accessibles par avion pourraient également être prioritaires.

ABSTRACT

The quality of life of inhabitants of Canada's North depends on the infrastructures that connect remote communities to the country's South and those that allow these communities to reduce transport and energy costs. Building these infrastructures are massive projects that have to be undertaken with caution, whether it be new roads, power lines or power plants. This is because the costs associated with such projects are immense, and their long-term effects are not well known in the northern context. Nonetheless, gaining a better understanding of what these infrastructures will generation socio-economically or how much they will cost can aid government stakeholders better understand what northern populations can gain.

Proposals for infrastructure development in Canada's North are gaining political traction, including a corridor connecting the northern regions of each of the country's provinces. Quebec is Canada's largest, northernmost province and would be pivotal in the construction of the corridor. Examining the historical phases of Quebec's northern development is crucial in assessing the challenges ahead. The first section of this thesis groups Quebec's infrastructure developments into three main phases, synthesizes each phase and critically compares them to the proposed Northern Corridor Concept (NCC). No research has yet examined the NCC's complementarity with Quebec's history of northern infrastructure development. While previous phases could be categorized as intraprovincial penetration corridors linking Northern to Southern Quebec, the NCC aims to develop an interprovincial economic corridor for landlocked provinces to be able to gain better sea access. Obstacles arising from the conciliation of past developments with the NCC include the unfitness of using existing infrastructures in Quebec for a Pan-Canadian corridor and differing development trajectories at the provincial and federal levels. Three route options for the NCC in Quebec are presented in this study. More generally, this paper outlines difficulties specific to subarctic remote corridor development.

As an essential form of transportation infrastructure, road connection is viewed as an important driver of economic development. However, for remote subarctic communities, it can also mean a huge change in their way of life. How large are the socio-economic benefits of road connection? The second section of this thesis uses census data from Northern Quebec and Labrador to assess the effects of road connection on municipalities connected between 1986 and 2016. Using a difference-in-differences regression model assorted with robustness checks, we find that road

connection is correlated with increased employment rates and educational attainment and decreased unemployment. While we also find positive and significant correlations between road connection and income in many specifications, that particular result is not robust when ensuring that error terms are not subject to cross-sectional dependence. Overall, our results support the conjecture that road connection of remote municipalities generates non-negligible economic benefits.

At a national scale, transitioning from non-renewable sources of energy to renewable ones is an important theme in Canada's government's platform. However, the investments required for such a transition are often said to be quite costly. In Canada, previous research has shown that a transition is economically feasible at the national level, but is an energy transition equally as feasible for each of Canada's provinces? The third section of this thesis uses energy use simulation data and a costing model to assess the infrastructure expenditures for a carbon-neutral transition for each of the country's ten provinces from now until 2060. By calculating the costs for five different scenarios and taking into account the savings incurred by lower fossil fuel consumption post-transition, we find that most of Canada's provinces stands to gain from a pan-Canadian energy transition by each capturing fossil fuel savings. We also find that generally, provinces that produce electricity using fossil fuels are set to benefit from more savings following a transition than provinces that currently produce electricity using renewable sources.

Canada produces most of its electricity using renewables. However, in remote communities that are not connected to Southern Canada's main grid, the quasi-totality of microgrids rely on fossil fuels to ensure electricity supply. How much would it cost to decarbonize all of these microgrids? The fourth section of this thesis uses a cost-based approach paired with a binary integer optimization model to find the least costly decarbonization solution for each off-grid settlement from now until 2050. By using wind speed and solar irradiance data together with future generation and storage cost estimates, our model determines whether solar or wind is more appropriate for a settlement and at which time period it is best to undergo a transition from fossil fuel generation to renewables. Our results show that the cost of decarbonizing Canada's remote microgrids are not prohibitive and which technology and implementation time period are cheapest for each settlement. We find that in 2020 wind turbines would be the cheapest option for most settlements, whereas in 2050 solar panels would be the cheapest option for most settlements. Settlements that currently use diesel of heavy fuel to produce electricity should consider undergoing a decarbonization as soon as possible, while those that use natural gas could wait until production and storage technologies become cheaper. Larger settlements and fly-in communities could also be prioritized.

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CHAPITRE 1 INTRODUCTION

Depuis un siècle, le Nord canadien fait l'objet de bien de la spéculation. Fonte des glaces et passage du Nord-Ouest, découverte de précieuses ressources minières et développement économique au sein de communautés éloignées sont des sujets qui suscitent de l'intérêt de différents paliers de gouvernement, de firmes privées et du public. Les infrastructures jouent un rôle indéniable quant à ces enjeux, que ce soit les routes et chemins de fer qui seront construits pour déplacer biens et personnes ou bien les façons que le Nord sera approvisionné en énergie. La qualité de vie des habitants du Nord est sans doute corrélée avec les infrastructures auxquelles ils ont accès (Nunavut, 2012). Or, entamer de nouvelles constructions sur un territoire aussi vaste que celui du Nord du Canada engendre des coûts bien plus prohibitifs par capita que dans des régions plus densément peuplées. Comprendre ce que ces infrastructures peuvent coûter et ce qu'elles peuvent engendrer comme effets économiques positifs est crucial à l'évaluation de la faisabilité de projets d'infrastructures futurs. L'étude ci-présente aborde ce sujet à la lumière de certains thèmes et contextes.

Différentes solutions sont envisagées pour améliorer la qualité de vie des habitants dans les régions éloignées du Canada, notamment la construction d'un Corridor économique pan-canadien qui connecterait le Yukon au Labrador (Sulzenko et Fellows, 2016). Ce corridor serait composé de routes, chemins de fer, gazoducs, oléoducs, lignes électriques et câbles de télécommunication d'un côté à l'autre du pays. Son but prétendu serait d'accroître le développement économique en régions nordiques en améliorant leur accessibilité. La littérature montre globalement que la construction d'infrastructures a des effets positifs sur l'économie locale et régionale (Calderón et Servén, 2004; Fan et Chan-Kang, 2005, 2008; Khandker et al., 2009; Olsson, 2009; Asher et Novosad, 2018; Barzin et al., 2018; Donaldson, 2018; Fingleton et Szumilo, 2019). Néanmoins, ces effets sont souvent très spécifiques à un cas particulier étudié dans chacune de ces études et peuvent difficilement s'appliquer à tout contexte, et encore moins au contexte nordique. Celui-ci se distingue par l'éloignement entre les communautés et la déconnexion entre celles-ci et le Sud du Canada. Avant d'investir de sommes importantes dans un nouveau projet de corridor d'infrastructures, il serait bien avisé d'en connaître davantage sur ces effets, et sur le projet du corridor nordique en général.

Une autre solution qui pourrait améliorer la qualité de vie des Canadiens vivant en régions éloignées est celle de la décarbonisation et l'atteinte du net-zéro carbone. Non seulement la consommation grandissante d'énergies fossiles met en danger l'unicité des écosystèmes nordiques du Canada, mais elle coute cher aux habitants du Nord (Jones et al., 2017). Toutefois, passer d'énergies fossiles vers des énergies renouvelables n'est pas sans sacrifice et requiert de nouveaux investissements en infrastructures de génération, de stockage et de transmission d'électricité. Certains chercheurs soutiennent que ces investissements seront catastrophiques (Režný et Bureš, 2019), alors que d'autres font état de coûts plus raisonnables dans l'atteinte d'objectifs de décarbonisation et net-zéro (Capros et al., 2014; D'Aprile et al., 2020; Heal, 2020). Comme l'impact d'infrastructures sur le développement économique, le coût d'une éventuelle décarbonisation dépend énormément des conditions spécifiques dans laquelle une étude est entreprise en raison des différences en sources d'électricité à remplacer et les coûts liés à différentes technologies renouvelables. Par exemple, les coûts de carburant en régions éloignées diffèrent de ceux en régions plus densément peuplées. Le Canada peut bénéficier d'une transition énergétique dans ses régions nordiques, et sans doute également dans chacune de ses provinces.

La littérature existante ne propose pas de solution pour comprendre plusieurs des enjeux économiques des infrastructures dans le Nord du Canada. Est-ce que le Corridor nordique canadien est une bonne idée? Quel est l'impact socio-économique de routes sur les communautés nordiques? Combien coûte l'installation d'infrastructures d'énergie renouvelables dans ces communautés? Est-ce qu'à l'échelle du Canada, une transition énergétique est plausible économiquement? Si oui, comment fait-on pour y arriver?

Cette thèse propose d'abord une comparaison qualitative entre l'historique des infrastructures dans le Nord du Québec et la proposition du Corridor nordique canadien. Ceci est accompagné d'une méthode statistique pour évaluer l'impact socio-économique des routes construites dans le Nord du Québec et au Labrador entre 1986 et 2016. Cette thèse emploie également une analyse à base de coûts similaire pour l'atteinte de net-zéro dans chaque province canadienne. Ceci est accompagné d'une méthode d'optimisation qui estime le coût minimal optimal pour une décarbonisation de tous les micro-réseaux électriques en usage dans les régions éloignées du Canada.

La première contribution de cette thèse cherche à analyser l'historique du développement du Nord du Québec. Elle regroupe tous les développements en infrastructure du Québec nordique en trois grandes phases, les synthétise d'une perspective historique et les compare de façon critique au Concept de corridor nordique. Aucune étude ne fait état de cette comparaison à ce jour. De plus, cette contribution souligne les difficultés propres au développement de corridors subarctiques en régions éloignées en utilisant le Concept de corridor nordique en relation avec l'histoire du Québec comme cas de figure pour les illustrer.

La deuxième contribution cherche à quantifier l'impact d'une connexion routière en région éloignée. Elle applique une méthode de régression des doubles différences à des données du recensement du Canada d'indicateurs de revenu, de population, d'éducation et du marché de l'emploi pour des communautés nordiques. Cette méthode cherche à isoler l'impact de la connexion routière d'une communauté nordique en contrôlant pour des effets fixes spécifiques à des tendances temporelles ou des tendances propres à certaines communautés. Elle a permis de déterminer que la construction d'une route a un effet socio-économique positif sur une communauté connectée qui continue de croître bien après la fin de la construction de la route.

La troisième contribution cherche à déterminer le coût total d'une transition énergétique pancanadienne. Elle emploie une analyse à base de coûts qui utilise les résultats de simulations de consommation d'énergie entre 2016 et 2060 pour chacune des provinces canadiennes afin d'évaluer les investissements et les économies possibles si chaque province entreprend une transition d'énergies fossiles vers des énergies renouvelables. Cette analyse permet de comprendre les différences entre les provinces et de cerner quelles politiques publiques devraient être mises en place pour stimuler une transition vers le net-zéro.

La quatrième contribution cherche à calculer le coût de décarbonisation de l'électricité pour chaque communauté éloignée au Canada. Elle utilise une méthode d'optimisation binaire en nombres entiers pour déterminer quel mode de génération d'électricité renouvelable serait la moins chère pour remplacer les centrales thermiques utilisant des carburants fossiles dans chacune des communautés éloignées du Canada qui dépendent d'un micro-réseau électrique. Cette analyse tient compte des changements en coûts de technologies renouvelables et des coûts de carburant qui sont économisés en décarbonisant entre 2020 et 2050. Non seulement cette contribution estime les coûts liés à une décarbonisation de l'électricité pour chaque communauté, mais elle permet également de conclure que ces coûts seraient loin d’être catastrophiques et qu’une transition le plus vite possible est généralement plus souhaitable.

La combinaison des différentes méthodes employées dans le cadre du travail de cette thèse permet de répondre aux questions posées plus haut. Chaque contribution propose des recommandations de politique publique qui viennent puiser des résultats obtenus dans les analyses qualitatives et quantitatives entreprises. Cette thèse offre des pistes claires et réalistes aux parties prenantes gouvernementales quant au développement routier et à la décarbonisation dans les régions éloignées du Canada, et pour le pays en son ensemble.

Le chapitre 2 de cette thèse consiste d’une revue de littérature qui explore les infrastructures et la nordicité, l’impact économique des infrastructures et les coûts liés à une transition énergétique et à la décarbonisation. Le chapitre 3 explique la démarche de l’ensemble du travail et la cohérence des articles de recherche par rapport aux objectifs de recherche. Les chapitres 4, 5, 6 et 7 présentent les première, deuxième, troisième et quatrième contributions respectivement. Le chapitre 8 est constitué d’une discussion générale et se suit d’une conclusion au chapitre 9.

CHAPITRE 2 REVUE DE LITTÉRATURE

Le chapitre précédent fait état de l'importance des infrastructures dans le Nord du Canada, et surtout de certains enjeux liés aux transports et à l'énergie durable. La littérature existante suggère que la construction d'infrastructures génère des coûts et des bénéfices. Élucider quels sont ces coûts et bénéfices dans le contexte nordique permet aux communautés éloignées de mieux prendre des décisions quant aux investissements dans de nouveaux projets. Ce chapitre consiste d'une revue de littérature qui examine trois sujets principaux : les infrastructures dans le Nord du Québec, l'impact économique d'infrastructures de transport et les coûts et impacts de la construction d'infrastructures dans un but de décarbonisation. Plutôt qu'un compte rendu exhaustif, cette revue de littérature critique synthétise les idées les plus pertinentes aux contributions de cette thèse.

Le thème des infrastructures du Nord est abordé dans la thèse sous l'angle de la nordicité (2.1) dans les deux premières contributions. La quatrième contribution, bien que touchant aux régions éloignées du Canada, possède également un lien important avec la nordicité de par le fait que la vaste majorité des communautés hors-réseau au Canada son effectivement nordiques. Le thème des infrastructures du Nord est également abordé sous l'angle du projet du Corridor nordique canadien (2.2), représentant sans doute l'avenir du développement d'infrastructures dans le Nord du Canada. Puisqu'il s'agit d'un nouveau projet, la section ci-présente répertorie ce qui a déjà été écrit sur le sujet.

Le thème de l'impact économique d'infrastructures de transport est amené en présentant en premier lieu le débat entourant la productivité générée par les investissements en infrastructures (2.3). Bien que ce sujet ne soit pas explicitement un des sujets d'un des articles de la thèse, il s'agit d'une partie importante de la littérature qui permet de comprendre la recherche subséquente portant sur l'effet d'une connexion routière. Cet effet est richement documenté, et la section ci-contre (2.4) montre clairement le type de conséquences que peut avoir une connexion routière en région éloignée.

Le thème des les coûts et impacts de la construction d'infrastructures dans un but de décarbonisation est approfondi à l'aide d'une revue de littérature (2.5) qui examine les cas d'estimation de coûts de décarbonisation à travers le monde. En raison des différences assez importantes entre ces estimations, la section en question étale l'état des lieux et nuance les différences entre les études précédemment entreprises.

À noter que les sections 2.1, 2.2, 2.4 et 2.5 reprennent presque textuellement les revues de littérature intégrées à chacun des articles de la thèse. Une synthèse à la fin de la section examine les liens entre différents aspects de la littérature existante.

2.1 Nordicité et le Québec

La définition de ce qui constitue le Nord québécois a évolué avec le temps. Les délimitations géographiques de la province de Québec ont changé en 1898 (Québec, 1898) avec l'élargissement de la province jusqu'à la Baie James, en 1912 (Québec, 1912) avec l'ajout de l'actuel Nunavik et en 1927 (Terre-Neuve, 1927) avec la redéfinition des frontières du Labrador. Ces changements ont également modifié ce qui peut être considéré comme le Nord du Québec. Jusqu'à la seconde moitié du XXe siècle, le Nord québécois pouvait être vaguement défini comme le Nord des Laurentides, les basses terres de l'Abitibi, la région du Lac-Saint-Jean et toute autre région septentrionale (Duhaime et al., 2012; Simard, 2017a). De nos jours, cette définition est largement désuète pour déterminer ce qui constitue véritablement le « Nord », car la plupart de ces régions se sont développées économiquement et technologiquement, les éloignant sémantiquement de ce qui serait considéré comme les vastes territoires inexplorés plus communément appelés « Nord québécois ».

Simard (2017b) compare chronologiquement quatre façons différentes de définir ce qui constitue le Nord québécois selon quatre chercheurs différents ayant étudié la nordicité québécoise. Il examine les différentes conceptions du Nord et les compare les unes aux autres, discutant des implications géographiques, sociologiques et anthropologiques de chaque perspective. Il note la valeur de chaque approche et essaie de déchiffrer l'intention ou l'idéologie derrière chacune. Ces méthodes tracent une voie plus claire vers l'identification des infrastructures qui peuvent être considérées comme véritablement nordiques avec le moins de biais idéologique possible et de manière fiable sur la base de mesures scientifiques palpables. Simard suggère que les travaux de Louis-Edmond Hamelin, avec ceux de Jules Dufour, sont les plus pertinents pour établir un cadre objectif de ce qui constitue le Nord québécois à partir de données géographiques et socio-économiques (Simard, 2017b). Cela rejoint les conclusions de Graham sur les différentes méthodes utilisées pour délimiter le Nord canadien. Graham conclut que la méthode de Hamelin demeure très utile pour délimiter ce qui constitue le Nord (Graham, 1990). McNiven et Puderer (2000) utilisent plusieurs des mêmes critères que Hamelin dans leur délimitation du Nord canadien et Vaguet et al. (2018) jugent la méthode de Hamelin pertinente pour délimiter le Nord à l'échelle mondiale. Il est également important de noter que le travail de Dufour s'appuie principalement sur celui de Hamelin. Compte tenu de l'héritage de la méthode de Hamelin dans la littérature existante et de sa fidélité à des indicateurs objectifs, la définition de Hamelin du Nord est grandement utile dans le cadre de cette thèse.

Hamelin est un pionnier concernant le Nord québécois et l'étude de la nordicité dans le monde. Son livre de 1975, Nordicité Canadienne, définit pour la première fois le mot « nordicité » comme les zones froides de l'hémisphère nord. Il définit également la nordicité comme variable, mesurable et évolutive dans le temps (Hamelin, 1975). Il a également posé une définition plus concrète et empirique de la mesure de la nordicité. Il a créé un indicateur connu sous le nom de "VAPO" ou "valeur polaire" qui peut mesurer la nordicité d'une ville ou d'une localité en générant un score de 1000, où 0 est "moins au nord" et 1000 est "plus au nord". La somme de dix critères évalués chacun sur des échelles de 1 à 100 donne un score total sur 1000. Six des dix critères sont strictement géospatiaux ou biophysiques (latitude, nombre de jours d'été, jours de gel annuel, niveau de pergélisol, niveaux de précipitations, végétation) et quatre critères sur dix sont socio-économiques (accès par route ou par bateau, accès par avion, densité de population, activité économique) (Hamelin, 1968). Tout comme une carte d'altitude topographique, les indicateurs VAPO de Hamelin permettent la création de ce qu'il appelle des "Isonords", ou de lignes sur une carte délimitant les zones d'un score VAPO donné. D'un score de 200 à 300, Hamelin considère la zone comme le « Bas moyen Nord » ; de 300 à 500, le « Haut moyen Nord » ; au-dessus de 500, le « Grand Nord » (Hamelin, 2000).

Compte tenu de ces indicateurs, il est important de noter que son modèle souligne le caractère évolutif de sa définition de la nordicité (Vaguet et al., 2018). Les indicateurs environnementaux pourraient changer progressivement et pourraient changer de plus en plus rapidement en raison du changement climatique. Néanmoins, ce sont les indicateurs socio-économiques qui ont le plus grand potentiel de changement en raison de nouvelles construction d'infrastructures ou de développement économique. Avec ce système de mesure, la construction même d'un projet d'infrastructure nordique a le potentiel d'abaisser le VAPO ou le niveau de nordicité de la région ciblée. L'activité économique, l'accès (aérien, routier ou ferroviaire) et la population ont tendance à fluctuer positivement avec l'arrivée de grands projets d'infrastructure dans une région. Ainsi, les scores VAPO devraient être mis à jour périodiquement pour qu'ils restent précis dans le temps. Cela repousserait progressivement la limite du Bas Moyen Nord vers le nord, selon les projets d'infrastructures du Nord construits au fil du temps. La méthodologie de Hamelin peut sans doute servir de moyen empirique de suivre le développement d'infrastructures dans le nord en recalculant le score VAPO pour différentes localités au fil du temps. L'aspect évolutif de cette échelle de mesure ne discrédite pas en soi cet outil comme méthode pour déterminer où se trouve le Nord et ce qui n'est pas « nordique », mais il est important de garder à l'esprit que ce qui est considéré nordique aujourd'hui ne le sera peut-être pas demain.

2.2 Le Corridor nordique canadien

En 2016, deux chercheurs de l'Université de Calgary, Andrei Sulzenko et Kent Fellows, ont publié un article décrivant une proposition pour ce qu'ils appellent le *Canadian Northern Corridor Concept* (Sulzenko et Fellows, 2016), ou le Corridor nordique canadien. Ce corridor consisterait d'une voie multimodale (routes, chemins de fer, ports maritimes, oléoducs, gazoducs, lignes électriques) qui connecterait toutes les régions nordiques de toutes les provinces du Canada, de la Colombie-Britannique au Labrador. Cet article et un article ultérieur ajoutant des précisions à cette proposition (Fellows et al., 2020) comparent le projet à des projets antérieurs qui traversent tout le pays. Outre Sulzenko et Fellows, d'autres chercheurs se sont également penchés sur les différentes facettes du Corridor nordique. Sulzenko et Koch (2020) ont exploré les voies politiques potentielles pour le projet ; Wright (2020) a défini son environnement juridique, surtout concernant le processus de consultation auprès de communautés autochtones; Rodrigue (2021) a étudié le corridor dans le contexte des systèmes de transport canadiens; Pearce et al. (2020) ont évalué les risques liés au changement climatique.

Par le passé, le gouvernement fédéral du Canada a favorisé des projets d'infrastructure de transport à grande échelle reliant différentes provinces, tels que le chemin de fer du Canadien National, le chemin de fer du Canadien Pacifique, la Voie maritime du Saint-Laurent et l'Autoroute transcanadienne. Ces quatre projets ont tous dépendu de la collaboration des provinces et du gouvernement fédéral. Depuis la fin des années 1960, il y a eu peu d'intérêt pour la construction d'infrastructures pancanadiennes, la plupart des grands projets d'infrastructure au Canada étant organisés au niveau provincial ou municipal (Fellows et al., 2020). Dans la proposition de Fellows et Sulzenko, les gouvernements fédéral et provinciaux créeraient un environnement pour faciliter les investissements privés. Ces investissements serviraient à financer les infrastructures constituant le corridor, atténuant ainsi les risques associés au projet et réduisant potentiellement les barrières pour attirer des investissements ultérieurs (Sulzenko et Fellows, 2016). Bien qu'un cadre de gouvernance stricte n'ait pas encore été établi, Sulzenko et Koch (2020) ont exploré les différentes options au niveau de réglementation qui pourraient être utilisées. Dans les cadres réglementaires proposés, la décision d'un tracé de corridor précis et l'examen d'une proposition de tracé sont des étapes incontestables du processus. La consultation des peuples autochtones s'intégrerait très probablement dans ces démarches.

Wright (2020) soutient avec éloquence que l'imprécision du Corridor nordique quant aux types d'infrastructures et aux emplacements choisis présenterait un problème sérieux pendant la consultation auprès des communautés autochtones dont les terres assujetties à un traité seraient affectées. Pour que le gouvernement consulte de manière significative une communauté au sujet d'un projet, la consultation doit porter sur une activité spécifique proposée dans un contexte spécifique. Parce que le Corridor nordique demeure un concept abstrait pour lequel il est difficile de prédire exactement quelles infrastructures seraient construites à quels endroits, il serait difficile d'avoir des consultations productives à son sujet. Outre consultations autochtones, le raisonnement mis en évidence par Fellows et al. (2020) consiste à limiter les dommages environnementaux en focalisant le développement des infrastructures sur une surface limitée sur de grandes distances. Rodrigue (2021) a examiné les défis environnementaux auxquels devront faire face les infrastructures construites dans le cadre du projet du Corridor nordique, notamment la dégradation hivernale et construire des infrastructures alors qu'il y a pergélisol. Pearce et al. (2020) ont cité les impacts du changement climatique sur la construction, l'exploitation et l'entretien du corridor tel que l'érosion des routes. Sulzenko et Koch (2020) ont souligné l'importance des évaluations d'impact environnemental dans la gouvernance du corridor.

2.3 La productivité des investissements en infrastructure

Aschauer soutint dans son article publié en 1989 (Aschauer, 1989) que le déclin de la productivité agrégée de certains pays était le résultat d'un déclin proportionnel en investissement public en infrastructures. Dans plusieurs ouvrages portant sur l'impact économique d'infrastructures routières, le préambule obligatoire par affirmation ou réfutation du propos d'Aschauer est devenu monnaie courante. Les trente dernières années de recherche empirique ont pondu une lucidité consensuelle s'étant installée par rapport au sujet. Il en ressort que l'effet des infrastructures sur la productivité est complexe et ambigu.

La revue de littérature de Gramlich (1994) fut la première à résumer les grands courants du débat controversé. Il énonce que celui-ci n'est pas résolu, tout en penchant du côté de la réfutation. L'auteur conteste la contention d'Aschauer en assimilant sa recherche à une simple corrélation plutôt que d'un lien causal palpable. Pour lui, il semble invraisemblable que des projets d'infrastructures publiques soient aussi rentables qu'Aschauer le prétend ; comment expliquer le manque d'enthousiasme d'entreprises privées à financer leurs propres autoroutes et ponts ?

Gramlich (1994) suggère que des analyses économétriques concernant les infrastructures publiques sont incommodes à accomplir, notamment parce qu'une valeur de marché est difficilement attribuable aux biens publics et qu'une grande partie des bénéfices associés à la construction d'infrastructures est immatérielle. Il avance que la question qui devrait être traitée n'est pas celle d'un manque d'infrastructures, mais plutôt celle des politiques gouvernementales en matière d'infrastructure. Il soutient ce point de vue en soulignant que certains types de projets d'infrastructures sont plus rentables que d'autres (maintenance et construction urbaine), et donc que ces types de projets devraient être priorisés si l'objectif est de maximiser la productivité économique. Il propose également que les entités sous-nationales, dans ce cas les états américains, détiennent les institutions nécessaires afin de décider quels projets financer pour avoir un stock d'infrastructures optimal. Cette proposition de décentralisation est appuyée par les résultats de Knight (2002), qui a trouvé que les subventions fédérales aux États-Unis réduisaient proportionnellement les dépenses au niveau sous-national, de sorte à avoir un effet net nul sur la somme résultante. Ceci laisse croire que si les entités sous-nationales avaient le plein contrôle du financement et de la construction de leurs infrastructures, elles pourraient mieux optimiser leurs stocks d'infrastructures. Cette conclusion justifie l'utilisation des péages comme méthode de financement optimal, passant le coût des infrastructures aux usagers. Cette solution est particulièrement pertinente sur un territoire où plusieurs usagers sont transitaires et n'y résident pas. L'exemple de l'Autriche vient à l'esprit, où les autoroutes sont financées par des péages. La topographie alpine du petit pays exige la construction de plusieurs tunnels, faisant augmenter exponentiellement les coûts de construction. En raison de sa localisation centrale en Europe, une grande partie des usagers des autoroutes autrichiennes sont étrangers. Pour ne pas pénaliser les résidents autrichiens, les péages se sont avérés un mode de financement conséquent.

Plusieurs études montrent que l'effet des infrastructures sur la productivité économique est nul - ou du moins plus chétif que le démontre Aschauer. Chandra et Thompson (2000) contribuent à leur tour au débat en ajoutant que pour les régions rurales, la littérature existante à ce moment n'indiquait pas clairement d'effet positif ou négatif. Leur analyse économétrique pointe dans cette direction : les municipalités traversées par une autoroute voient leur productivité augmenter alors que celles qui sont adjacentes à celles qui sont traversées voient leur productivité diminuer. Ceci mène à penser que le résultat net sur la productivité n'est pas forcément significatif et bien plus ambigu. Harchaoui et Tarkhani (2003) expliquent que la productivité augmente significativement et proportionnellement aux investissements publics seulement dans certaines industries. Dans le même ordre d'idées, Michaels (2008) trouve que la construction d'infrastructures, plutôt que de faire augmenter la productivité de façon générale, fait augmenter la productivité dans certains secteurs de l'économie et la fait baisser dans des régions avec moins de main d'œuvre qualifiée. Duranton et Turner (2012) calculent une modeste relation entre la construction d'un kilomètre d'autoroute ou de l'achat d'autobus et la population d'un centre urbain. Holl (2004) illustre les changements d'emplacements de l'industrie manufacturière qui ont lieu après la construction d'autoroutes. Fretz et al. (2017) illustre la migration de main-d'œuvre éduquée vers les banlieues associée aux nouvelles autoroutes. Tous ces articles contribuent au débat et le font pivoter vers certains éléments spécifiques de l'impact des infrastructures. Certains ne trouvent aucun gain net appréciable en productivité globale.

Chaque étude semble montrer un effet économique global dans une direction ou l'autre, infirmant ou confirmant l'opinion d'Aschauer. Ce n'est pas pour dire que les infrastructures construites ne changent pas le paysage économique des régions affectées. L'ambiguïté des résultats semble indiquer que la productivité globale n'est pas directement affectée par l'investissement en infrastructures publiques – si oui, que faiblement. S'il y a consensus, c'est que l'affirmation d'Aschauer fut potentiellement exagérée. Il est indéniable que la construction de routes modifie significativement la composition économique d'une région au niveau de la population, de la main d'œuvre, des secteurs d'activité et des lieux de concentration de la productivité.

2.4 L'impact socio-économique des routes

L'impact du développement de liens routiers sur la croissance économique d'un pays a fait l'objet d'un large éventail de recherches. Qu'il s'agisse de réduction des inégalités sociales (Calderón et Servén, 2004), de hausse des salaires (Donaldson, 2018 ; Fingleton et Szumilo, 2019), de facilité à exporter des biens (Ng et al., 2019), de croissance des entreprises (Barzin et al. , 2018), les changements de population (Iacono et Levinson, 2016) ou les changements possibles de la productivité (Aschauer, 1989 ; Gramlich, 1994 ; Chandra et Thompson, 2000 ; Harchaoui et Tarkhani, 2003 ; Sahoo et Dash, 2009, 2012 ; Sahoo et al ., 2010 ; Konno et al., 2021), la littérature existante tend à montrer des effets significatifs de la construction d'infrastructures sur le développement économique.

Il a été démontré que la connexion routière, et plus particulièrement l'accès aux routes rurales, génère des avantages tangibles pour les communautés nouvellement connectées en réduisant le taux de pauvreté (Fan et Chan-Kang, 2005, 2008 ; Khandker et al., 2009), en améliorant les opportunités d'emploi local (Olsson , 2009), améliorant l'accessibilité des communautés éloignées à l'école et aux soins de santé (Asher et Novosad, 2018) et catalysant la compétitivité économique des régions connectées (Démurger, 2001). Cependant, la construction de routes pour relier les zones éloignées aux centres plus peuplés peut être très coûteuse (Asher et Novosad, 2018) et avoir le potentiel de changer à jamais le tissu social et culturel des communautés touchées (Cheers, 1993 ; Chung, 1988). Pour ces raisons, la construction d'une route reliant une communauté auparavant isolée au réseau routier principal peut devenir une pomme de discorde entre ses habitants. Ainsi, les gouvernements et les décideurs qui envisagent de construire des routes doivent comprendre exactement ce que ces communautés ont à gagner en sacrifiant certains aspects de leur mode de vie.

Comme Gobillon et al. (2007) l'ont montré, une abondante littérature s'est concentrée sur l'impact du développement des routes urbaines et suburbaines sur la connectivité physique des travailleurs dans une ville avec des emplois dans une autre ville dans le contexte nord-américain. La connexion physique offerte par une nouvelle route permet de réduire l’inadéquation entre les emplois et les employés. Berg et al. (2015) suggèrent que ces conclusions peuvent être appliquées à une variété de contextes. En effet, le mécanisme de l'inadéquation spatiale s'applique à de nombreuses configurations spatiales différentes, et pas seulement au développement urbain américain. Ce mécanisme d’inadéquation sociale "implique le rôle des coûts de transport élevés qui dissuadent les chômeurs d'accepter des emplois éloignés, les effets néfastes des longs trajets quotidiens sur la productivité ou de la baisse de la productivité, ou des coûts de recherche d’emploi élevés qui rendent moins efficace l'adéquation entre chômeurs et emplois". Bien que l'argument de la réduction des longs trajets quotidiens ne puisse pas vraiment s'appliquer au contexte du Nord canadien, les coûts de transport élevés qui dissuadent les chômeurs d'accepter des emplois éloignés pourraient être pertinents pour les municipalités arctiques et subarctiques. Une meilleure correspondance spatiale grâce à un accès plus facile aux municipalités éloignées peut permettre aux organisations locales d'économiser sur les coûts de recherche et d'accéder à un plus grand bassin de candidats - ceux-ci qui seraient autrement dissuadés par des coûts de transport prohibitifs vers une localité éloignée.

De meilleurs salaires et la réduction de la pauvreté ont été associés à la construction de routes et à l'accès routier. Fan et Chan-Kang (2005, 2008), Khandker et al. (2009), Emran et Hou (2013), Donaldson (2018) et Fingleton et Szumilo (2019) associent la construction d'infrastructures dans les zones rurales à des salaires plus élevés et à une meilleure qualité de vie. Les réductions de la pauvreté sont une conséquence de la diversification de l'économie locale (Fan et Chan-Kang, 2005 ; Khandker et al., 2009), des nouvelles opportunités d'emploi qui découlent de l'accès à d'autres parties d'une région (Olsson, 2009), des salaires plus élevés grâce à la production (Donaldson, 2018) et un meilleur accès aux marchés nationaux et internationaux (Emran et Hou, 2013). L'investissement dans la construction de routes profite également davantage aux pauvres qu'aux non pauvres (Khandker et al., 2009), en raison d'un coût de la vie moins élevé.

Le transport et un meilleur accès à l'éducation ont fait l'objet de diverses études. Vasconcillos (1997) souligne l'importance des accès routiers physiques pour permettre aux élèves de se rendre à l'école. Stifel et al. (2016) expliquent que l'accès aux écoles est souvent un avantage négligé de la construction de routes qui n'est pas pris en compte dans les études examinant le développement économique. Jacoby et Minten (2009) et Khandker et al. (2009) évaluent quantitativement l'impact des routes sur la fréquentation et le niveau d'instruction dans les villages de pays moins développés, trouvant des corrélations positives. Toutes ces études soulignent de manière différente une explication assez similaire de cette corrélation : un meilleur accès physique et des coûts de transport réduits facilitent l'accès à l'éducation des habitants des zones nouvellement connectées.

2.5 Transition énergétique et coûts en infrastructures

Aucun pays au monde n'a encore effectué une transition à partir de sources d'énergie non-renouvelables vers des sources renouvelables pour produire de l'électricité. Les gouvernements du monde entier font face à de la résistance lorsqu'ils proposent des projets de transition complète en raison du coût supposément élevé de la transition. Cependant, un corpus de littérature en évolution postule qu'une transition énergétique n'est pas nécessairement aussi coûteuse ou déstabilisante qu'on pourrait le penser et peut invoquer d'importants avantages économiques à long terme.

Plusieurs chercheurs ont cherché à comprendre quel impact aurait une transition énergétique sur l'économie mondiale. D'Alessandro et al. (2010) soulignent qu'une transition progressive vers des sources renouvelables serait durable et n'entraînerait pas automatiquement une stagnation ou une décroissance du PIB (produit intérieur brut) mondial. Garcia-Casals et al. (2019) suggèrent qu'une transition énergétique mondiale de 2018 à 2050 entraînerait une augmentation du PIB mondial, du PIB spécifique à chaque pays et du nombre d’emplois disponibles. Nieto et al. (2020) affirment non seulement qu’une transition énergétique entraînerait des augmentations du PIB, mais aussi qu’elle pourrait être le seul moyen d'assurer une certaine croissance du PIB à l'avenir. Bogdanov et al. (2021) affirment que l'électricité à faible coût est un moyen réalisable de répondre à la demande énergétique mondiale tout en limitant l'impact du changement climatique. Ils estiment que les coûts d'infrastructure pour produire et distribuer l'énergie renouvelable constitueront la plus grande partie des dépenses énergétiques à l'avenir, car la consommation de carburant deviendrait quasi inexistante et ne représenterait donc pas un coût significatif. Ces prévisions de coûts d'infrastructure sont similaires à celles de Režný et Bureš (2019), qui ont calculé qu'une transition énergétique mondiale nécessiterait un ratio investissement/PIB proche de celui typique de temps de guerre.

Lorsque l'on examine les contextes spécifiques à un pays ou à une région de l'impact économique de la décarbonisation, les analyses semblent présenter des conclusions plus ou moins claires. Au niveau macro-régional, Victoria et al. (2020) confirment l'ampleur de ces dépenses pour l'Europe, mais soulignent les importantes réductions de coûts qui pourraient être obtenues en investissant dans la décarbonisation à l’aube de la transition. Capros et al. (2014) ont constaté que pour l'UE (Union européenne), un objectif de réduction des émissions de 80 % ne nécessiterait que des coûts s'élevant à 1 % du PIB ou moins de 2015 à 2050. D'Aprile et al. (2020) indiquent qu'un chiffre similaire de 1 % d'investissements supplémentaires est nécessaire pour mener à bien une transition énergétique dans l'UE. À l’échelle de pays individuels, plusieurs études ont évalué l'impact économique d'une transition. Sadika et al. (2018) affirment qu'une transition vers des systèmes d'énergie renouvelable serait l'option la moins coûteuse pour le Pakistan dans un avenir proche. Kilickaplan et al. (2017) constatent qu'une transition énergétique, bien que coûteuse au départ, permettrait à la Turquie de s'affranchir des importations de carburants et de réduire significativement les coûts de production d'électricité d'ici 2050. Fortes et al. (2019) concluent que les coûts en capital d’une transition au Portugal entre 2015 et 2050 ne seraient pas plus grands que les dépenses dans le secteur pétrolier et gazier aujourd’hui. Au Royaume-Uni, Allan et al. (2020) affirment même que la transition énergétique jouera un rôle clé dans la reprise économique du coronavirus.

Au sujet de transition énergétique, l'Allemagne est particulièrement intéressante, car le pays mène déjà la transition énergétique vers le solaire et l’éolien la plus complète au monde. Puisque les cadres institutionnels et infrastructurels nécessaires à une transition énergétique sont déjà en place, les prévisions concernant l'impact économique de leur transition énergétique sont moins spéculatives que dans les pays où une telle transition n'a pas encore été entreprise. Lehr et al. (2012) constatent qu'une transition énergétique pourrait créer des emplois en Allemagne d'ici 2030. Blazejczak et al. (2014) ont prédit qu'à la même date, l'Allemagne connaîtra également une croissance économique plus élevée en raison de l'expansion des énergies renouvelables. Andor et al. (2017) font état de l'inefficacité du système allemand de tarifs d’achat pour l’électricité renouvelable et l'augmentation subséquente des coûts de l'électricité depuis 2010, quelques ceux des plus élevés des pays de l'OCDE pour résidents et entreprises allemand. Unnerstall (2017) reconnaît les inconvénients de la transition énergétique allemande mais propose une justification. Il dit que la transition énergétique de l'Allemagne a été initialement présentée comme un projet pour remplacer l’énergie nucléaire. Bien que l'énergie nucléaire ne soit pas une source d'énergie renouvelable, ce n'est pas non plus un combustible fossile et elle ne produit pas d'émissions de carbone. Ainsi, les énergies renouvelables installées au cours de la première décennie de la transition ont été mises en service pour remplacer les centrales nucléaires, et non la capacité de production d'électricité à partir de combustibles fossiles. En tant que pionnier des technologies vertes, l'Allemagne a effectué la transition lorsque le prix des technologies d'énergie renouvelable était à son plus haut. Unnerstall calcule le coût d'une transition si elle se produisait entre 2017 et 2030 et constate que les mêmes efforts de décarbonisation déployés jusqu'à présent ne coûteraient qu'environ 0,15 % du PIB du pays s'ils avaient été entrepris maintenant plutôt qu'avant. Son article montre également le caractère évolutif des projets de transition énergétique : en raison de l'évolution rapide des coûts des technologies des énergies renouvelables, une transition demain est moins chère qu'une transition hier.

Heal (2020) effectue une modélisation similaire pour le contexte américain avec quelques paramètres supplémentaires. Il tente de comprendre le coût de la transition de toutes les capacités de production d'électricité à partir de combustibles fossiles par la production solaire et éolienne aux États-Unis entre 2020 et 2050. Pour rendre son analyse plus sensée, il a ajouté les coûts de stockage d'énergie et les coûts de transmission au coût total, tout en soustrayant les coûts des combustibles fossiles et les actifs bloqués qui devraient être remplacés. Avec un coût total annuel de 6,1 milliards de dollars, Heal affirme qu'une transition énergétique aux États-Unis représenterait environ 0,02 % de dépenses supplémentaires du PIB après déduction des économies de carburant et des économies des infrastructures qui n'ont pas à être remplacées. Ainsi, une transition énergétique n'est probablement pas d'un coût catastrophique pour les États-Unis.

Au total, la règle cardinale pour établir le coût de la transition semble être de prendre en compte les spécificités du contexte d'un pays ou d'une région. Chaque entité politique a des particularités réglementaires et économiques qui font d’elle un cas unique. Ceci justifie l’application de modèles économiques à un territoire spécifique afin d’en connaître les coûts propres à son contexte.

2.6 Synthèse

Chaque section de la revue de littérature ci-dessus approfondit un sujet de recherche en particulier. Les thèmes abordés sous forme de cinq revues de littérature font ressortir quelques réflexions qui mettent en commun ces sujets de recherche.

Il ressort du Concept du corridor nordique (2.2) qu’il reste plusieurs aspects du projet qui doivent être mieux définis pour que sa construction aille de l’avant. La nouveauté de la proposition implique que le territoire qui sera défriché par les différents modes de transport et de communication sera grandement affecté. En utilisant la logique des VAPO de Hamelin (2.1), on devra se poser la question de comment le projet du corridor nordique va influencer le niveau de nordicité des contrées dans lesquelles il passera. Puisque les indicateurs socio-économiques seront décidément altérés, il est possible d’imaginer que certaines des régions affectées par le nouveau corridor ne seront peut-être plus « nordiques » à la fin de sa complétion.

La productivité (2.3) et le développement économique (2.4) sont présentés comme deux résultats distincts de la construction d’infrastructures. Ce qui distingue ces deux sections est le concept de la « connexion routière » avant tout. La section 2.3 discute l’investissement en infrastructures de façon générale et de façon peu granulaire, où une région élargie qui connaît davantage d'investissements publics connaît potentiellement plus de productivité. En occurrence, la section 2.4 discute également d'investissement public, mais sous forme de la construction d'un lien routier qui connecte une localité spécifique à un réseau routier plus dense. L'investissement visé n'est donc pas entrepris pour une région géographique élargie, mais plutôt pour un tracé très spécifique entre deux points. Les effets positifs cités dans la section 2.4 sont moins mitigés que ceux concernant la productivité, possiblement un résultat de ce ciblage plus précis.

Les coûts de la décarbonisation (2.5) d'un réseau électrique d'un pays ou d'une région sont dépendants des particularités de l'entité géographique dans laquelle la décarbonisation est mise en œuvre. Il en est de même pour les impacts de la décarbonisation sur l'économie. Néanmoins, les pistes d'analyse présentées dans la section 2.5 résument surtout des coûts à un niveau national ou supranational. La section 2.4 montre les effets spécifiques de la connexion de localités éloignées à un réseau routier plus dense. Il est possible que les mêmes conclusions puissent être tirées quant à la connexion d'un micro-réseau électrique éloigné à un réseau électrique plus dense. De plus, on pourrait se poser la question de si la création d'un réseau électrique complètement autonome dans une communauté hors-réseau aurait le même effet économique qu'une connexion au réseau plus dense. Il serait également intéressant de savoir si l'investissement en infrastructures énergétiques dans une optique de décarbonisation a un effet sur la productivité tel que proposé dans la section 2.3 pour des infrastructures routières.

CHAPITRE 3 DÉMARCHE ET ORGANISATION

La revue de littérature dans le Chapitre 2 expose certains aspects du Nord les infrastructures qui peuvent y être construites et certains des impacts et coûts qui y sont associés. Cette thèse cherche à élucider quels sont les avantages et désavantages de la construction d'infrastructures dans le Nord du Canada. Autant le transport que l'énergie sont des enjeux criants du développement du Nord, revenant donc à nous questionner : Quel est l'impact économique d'un lien routier? Combien coûterait le passage d'énergies fossiles à renouvelables? Les deux questions ci-contre sont générales et doivent se poser en fonction d'une région géographique spécifique, dans ce cas le Nord du Canada. Que ce soit des liens routiers ou des moyens de production d'électricité renouvelable, plusieurs interrogations à leur sujet restent béantes. Cette thèse cherche à combler certaines lacunes dans la recherche existante en répondant à ces deux questions à la lumière de deux thèmes, la nordicité et le fédéralisme dans le contexte canadien. Ces questions se conjuguent en différentes sous-questions propres à ces thèmes qui donnent lieu chacune à un chapitre de cette thèse, de même qu'en objectifs de recherche répondant à ces questions :

Chapitre 4 : Quel serait la portée d'un projet d'infrastructures nordiques d'envergure fédérale sur le réseau existant?

- L'objectif de cette analyse comparative est d'utiliser le cas du Corridor nordique au Québec pour comprendre sa portée pour les parties prenantes de projets d'infrastructures publics.

Chapitre 5 : Quel est l'impact socio-économique d'une connexion routière sur une communauté nordique?

- L'objectif de cette analyse économétrique est d'estimer l'impact d'une connexion routière sur une communauté nordique pour les habitants de cette communauté.

Chapitre 6 : Combien coûterait à chaque province canadienne une transition énergétique de tous les secteurs de consommation énergétique de l'économie?

- L'objectif de cette estimation de coûts est de donner un ordre de grandeur aux dépenses qui seront nécessaires pour une transition énergétique pancanadienne.

Chapitre 7 : Quels seraient les coûts et bénéfices associés à la décarbonisation de l'électricité pour chaque communauté éloignée/nordique?

- L'objectif de cette modélisation est de déterminer quelle technologie est la moins chère et quel coût serait engendré par une décarbonisation du micro-réseau d'une communauté nordique.

Le Chapitre 4 de cette thèse est une étude de cas qui agit comme entrée en matière pour de ce qui est d'infrastructures nordiques, que ce soit des routes, lignes électriques ou chemins de fer. Il introduit le concept de nordicité et le place dans un cadre de référence canadien. En utilisant le Nord du Québec comme cas, ce chapitre répertorie toutes les infrastructures existantes d'un point de vue historique et les catégorise en phases de développement. Ces phases sont comparées au projet pancanadien et fédérateur d'un Corridor nordique pour déterminer la faisabilité de celui-ci sur le territoire québécois et les effets potentiels de ce projet. La comparaison entre les phases de développement passées et la proposition d'un nouveau corridor n'avait jamais été abordée. L'analyse qualitative entreprise dans ce chapitre offre d'abord des pistes de solution pour un tel corridor, mais aussi peut être utilisée comme référence pour des analyses similaires dans d'autres provinces qui ont connu des phases de développement semblables. Les relations entre le gouvernement provincial et le gouvernement fédéral, de même que l'axe fédéralisme canadien-nationalisme québécois, sont abordés. Cet article a été publié dans la revue *Arctic* en mars 2022.

Le Chapitre 5 est la suite logique du chapitre précédent en ajoutant une dimension quantitative à l'analyse d'infrastructures nordiques. En estimant certains effets socio-économiques de la connexion routière de communautés nordiques au Québec et au Labrador, ce chapitre se départit d'un point de vue global pour élucider ce qui se passe à plus petite échelle. En examinant le comportement d'indicateurs en éducation, chômage et de salaire, cette section de la thèse fait état pour la première fois d'effets mesurables d'une route en contexte nordique. Cette analyse est pertinente pour le reste du Canada, mais également pour toutes les régions nordiques du monde et potentiellement pour toutes les régions qui ont une faible densité d'infrastructures. Cet article a été soumis à la revue *Transport Policy* en Septembre 2021 et est en révision.

Le Chapitre 6 se veut une ouverture vers de nouvelles contrées dans la recherche en reprenant certaines des thématiques des trois chapitres précédents. Cette analyse de coûts utilise un modèle appliqué à toutes les provinces du Canada et à tous les secteurs consommant de l'énergie plutôt que seulement celui de la production d’électricité. Cette analyse basée sur des résultats de simulation est unique et aucune littérature n’aborde ce sujet spécifiquement. Le chapitre comporte une section importante touchant aux politiques publiques qui peuvent stimuler une transition énergétique pour chaque palier de gouvernement. Le thème de fédéralisme et de coopération entre les provinces y est présent, faisant écho aux enjeux du Corridor nordique du Chapitre 4. Cet article a été publiée dans la revue *Energy Policy* dans l’édition de mai 2022.

Le Chapitre 7 adopte un autre angle d’attaque pour analyser la construction d’infrastructures au sein de communautés éloignées en explorant les coûts liés à la décarbonisation de micro-réseaux électriques qui utilisent présentement des énergies fossiles, notamment avec des panneaux solaires et des turbines éoliennes. Puisque la vaste majorité de communautés éloignées sont en milieu nordique, cette analyse concorde avec celle du chapitre précédent et reprend plusieurs concepts du Chapitre 4. En raison de la nouveauté de ces technologies en milieu nordique, il était plus approprié d’évaluer les coûts futurs que d’essayer de comprendre les impacts du passé. Utiliser un modèle d’optimisation pour déterminer quelle technologie serait la meilleure pour chaque communauté n’a jamais été entrepris auparavant, faisant de ce chapitre une contribution intéressante à la littérature grandissante concernant la décarbonisation au Canada. Cet article a été soumis à la revue *Energy Journal* en février 2022 et est en révision.

Les chapitre 4,5 et 7 sont directement liés au thème du Nord du Canada, alors que le Chapitre 6 ne l’est pas. Cependant, ce dernier est le résultat d’une réflexion plus poussée concernant le sort de politiques énergétiques imminentes au Canada. Le Chapitre 4 analyse de façon critique un projet qui a indéniablement une composante énergétique importante. Le Corridor nordique canadien consiste d’un projet énergétique qui solidifierait probablement les infrastructures liées à la production et la vente d’énergies fossiles. Or, le Chapitre 6 prône l’utilisation de connections infrastructurelles pancanadiennes pour répandre l’utilisation d’électricité propre à travers le Canada. Le Chapitre 7 retient les méthodes du Chapitre 6 et les applique au contexte nordique, de sorte à faire le lien entre le thème du Nord exploré dans les chapitres 4 et 5 et le thème de la transition énergétique exploré dans le Chapitre 6.

L’avenir du Canada dépend partiellement de ce qui va se passer dans le Nord et dépend largement de quelles politiques énergétiques seront mises en place dans un futur proche. La construction d’infrastructures est une des seules manières d’accroître l’accessibilité de régions éloignées et d’améliorer la qualité de vie de leurs habitants. Chacun de ces quatre chapitres consiste d’une contribution différente à la littérature existante. Néanmoins, chacun d’eux permet de mieux comprendre des sujets chauds propres au développement d’infrastructures d’énergie et de transport. Les synergies entre les différents résultats des quatre chapitres sont discutées dans le Chapitre 8. Les conclusions de la thèse et les recommandations pour de la recherche future sont présentées dans le Chapitre 9.

CHAPITRE 4 ARTICLE 1: SUBARCTIC CORRIDORS IN NORTHERN QUEBEC: IS THE CANADIAN NORTHERN CORRIDOR CONCEPT ALIGNED WITH QUEBEC’S HISTORICAL DEVELOPMENT?

T. Stringer et M. Joanis ont écrit cet article. Celui-ci sera publié en mars 2022 dans la revue *Arctic*.

4.1 Introduction

Canada’s Great North has been the subject of much speculation as modern technology allows the sparsely populated region to become more accessible. Provinces and territories with a stake in the Great North have engaged in reflective public debates about how to develop their Northern regions, while some have already proposed more comprehensive infrastructure projects, such as Ontario’s Ring of Fire road planning (Ontario Chamber of Commerce, 2014), Yukon’s Resource Gateway Project (Government of Yukon, 2021) or the Northwest Territories’ Arctic and Northern Policy Framework (CIRNAC, 2019). Quebec, in particular, has brought this debate to the forefront of its politics with the introduction of the province’s Plan Nord in 2011, and in 2020 with the announcement of a new James Bay Region development project, “La Grande Alliance”, proposing better maintenance of existing northern roads as well as the construction of new roads connecting southern transportation infrastructures to isolated towns.

Uniting the country through infrastructure development has a long history in Canada. A transcontinental railway was one of the conditions of the first constitution of Canada in 1867, the British North America Act. In the 1930s, the federal government contributed to the construction of highways by provinces by funding 50% of the expenditures. The goal was to build a road crossing the country without having to enter the United States. The construction of the Trans-Canada highway in the 1950s was driven by the federal government’s will to construct a high-quality highway connecting both sides of the country in the shortest distance possible as well as its generous funding (Turgeon and Vaillancourt, 2002). Since the 1960s, the idea of a northern infrastructure corridor in Canada has been floated around as a new path to the country’s development (Rohmer, 1970; National Post, 2016). Imagined as a northern multimodal corridor spanning Canada from one coast to another, the concept has gained traction amongst members of Canada’s political class (CBC News, 2018). In their 2016 article, Sulzenko and Fellows formally present their vision of the Canadian Northern Corridor Concept (NCC), underlining the advantages and disadvantages of an economic corridor through Canada's North spanning from British Columbia to Labrador consisting of power lines, railways, roads, pipelines and telecommunication cables (Sulzenko et al., 2016). Canada's 2019 Federal Election brought forth a certain level of enthusiasm for a new energy corridor amongst politicians (Global News, 2019), but also highlighted the divisiveness of new energy propositions in a political climate of environmental urgency (Barlow and Nadeau, 2019). The proposed multimodal corridor is a base model for territorial development that could be socially, economically, politically and environmentally beneficial for Canada according to Fellows et al. (2020).

Since the post-war era, many projects to develop Quebec's North have been proposed. Some have been put into action to "colonize" (Duhaime et al., 2013) the North and exploit its plethora of natural resources, whether it be Hydro-Quebec's projects in the James Bay region or the more recent Plan Nord. Since Hydro-Québec's massive northern hydroelectric projects in the 1970s, there has been a political will by Quebec's elected officials to make northern Quebec more accessible to prospecting interests and inhabitants. The rollout of grand infrastructure projects to connect the sparsely populated North to the more densely populated South has been a result of this political will. In contrast, the Northern Corridor Concept promotes communication between Quebec and its neighbouring provinces, Ontario and Newfoundland-and-Labrador (Sulzenko and Fellows, 2016).

A handful of researchers have pored over different facets of the proposed Northern Corridor Concept. Sulzenko and Koch (2020) have explored potential policy pathways for the project; Wright (2020) has established its legal environment in terms of indigenous consultation; Rodrigue (2021) has studied the corridor in the context of Canadian transport systems; Pearce et al. (2020) attempted to evaluate the project's risks related to climate change. While existing literature has sought to effectively probe critical features of the Northern Corridor Concept for all of Canada, no research has specifically touched upon Northern Quebec, even less examined the complementarity between historical infrastructure development in Quebec and the proposed Northern Corridor Concept. What infrastructures were built in Northern Quebec? What northern development plans were put into place? Is the Northern Corridor Concept aligned with Quebec's past Northern infrastructure projects? Is the political vision of the Northern Corridor Concept similar to that of past projects? Are the geographical outlines of existing infrastructures and proposed infrastructures reconcilable? Are there opportunities that could arise from the complementarity of historical projects and future projects?

This article will attempt to answer these questions by defining “northern infrastructure”, grouping these infrastructures into an original three-phase framework and comparing major historical transportation infrastructure developments in Northern Quebec to the infrastructure development proposed by the Canadian Northern Corridor Concept. Further, it will propose three options for future corridor planning in the region.

The first part of the article will describe our methodology. The second part of the article will delimit what constitutes northern Quebec geographically by defining nordicity in this particular context. The third part will enumerate and group into phases the existing transportation infrastructures that are located in what is defined in the second part as Quebec’s North. The fourth part will analyze the historical phases of northern infrastructure development for Quebec’s North by surveying a wide-reaching body of historical and geographical literature. The fifth part will present the Northern Corridor Concept and offer three outlines that make use of existing infrastructures in Northern Quebec. The sixth part will critically compare the historical Northern development phases analyzed in part four against the Canadian Northern Corridor Concept described in part five.

4.2 Part 1: Methodology

We define three original historical phases of large-scale transportation infrastructure development in northern Quebec as cases to be compared against the proposed Canadian Northern Corridor Concept. For the purpose of this article, a “northern infrastructure” is defined as an infrastructure that connects two points (railways, roads and high-voltage power lines) and that either crosses or is above the limit between northern and southern Quebec as defined further.

We then systematically survey the existing infrastructures corresponding to the definition of a “northern infrastructure”. This enumeration was achieved by filtering all the existing infrastructures in Quebec by whether they abided by the above-prescribed definition. Using data from Université Laval’s GéoIndex database and QGIS 3.18, we geographically determined which infrastructures were considered “northern” by mapping the coordinates of the infrastructures. Data points that have a latitude with a higher value than the North-South delimitation were considered to be northern. We then generated a map showing Quebec's northern infrastructures overlayed by the delimitation of the North and the South (Figure 4.1). We also generated a map showing northern infrastructures overlayed by the proposed route of the Northern Corridor Concept (Figure 4.2). These representations are unique in that they visually identify and define Quebec's northern infrastructures using an empirical method to quantify nordicity. We generated a map showing three corridor options using existing infrastructures in Northern Quebec (Figure 4.3). All three figures can be found in the Appendix.

To this day, there is no clear delimitation or definition in the literature of the phases of infrastructure development in Northern Quebec. We address this by dividing Quebec's northern infrastructures into three distinct phases. We use purposeful sampling to select the historical cases. This nonprobability selection method employs specific criteria to create a sample of objects sharing predefined traits (Patton, 1990). We chose to define each case as a group of northern infrastructure projects that form together a phase of infrastructure development in Quebec's history. Each phase is defined by the timeframe in which the infrastructures were built and common objectives shared by the aggregated infrastructure projects of a grouping. The common objective criteria are the following: the types of infrastructures built, the types of resources extracted, the level of involvement of Quebec's government in the construction and the ownership of the infrastructures. Geographical progression into more northern territories was also taken into account. New infrastructure developments are typically adjacent to existing networks. Thus, when analyzing infrastructure development chronologically, newer infrastructures tend to further penetrate the north than their predecessors. We primarily use the timeframe criterion to separate the broad periods of Quebec northern infrastructure development sharing common traits. We group together infrastructures that were built in the same time period while having certain common objectives. The phases and periods could overlap by a few years, but each had to represent a novel and distinct phase in Quebec's northern infrastructure development that could easily be distinguishable from the other phases. After clustering the master list of enumerated infrastructures using the criterion of each construction, we created three tables (Tables 4.1, 4.2 and 4.3). The Northern Corridor Concept would represent a hypothetical novel phase of development for the Province of Quebec if the proposal was carried out. It was considered as such in the analysis.

We make the comparison between Quebec's history of development and the proposed corridor by using two frameworks defining the stages of a transportation corridor or economic corridor. A transportation corridor is “a coordinated bundle of transport and logistics infrastructure and services that facilitates trade and transport flows between major centers of economic activity.” (Kunaka and Carruthers, 2014) On the other hand, an economic corridor “connects economic agents along a defined geography” and is “integral to the economic fabric and the economic actors surrounding it.” (Brunner, 2013) Both definitions complement each other, the first underlining the role of infrastructures and the second the economic dimension. Each of the four phases of development is categorized according to two concurring corridor frameworks to reflect this complementary approach: Comtois’ classification of transportation corridors and Banomyong’s stages of economic corridor development.

The former defines three types of transportation corridors (Comtois, 2012):

- Penetration Corridor: “Construction of an infrastructure connecting two points with a goal of transporting goods, equipment and manpower between those two points.”
- Chain Corridor: “Sequence of transportation corridors in which the entrance to one is the exit of another in an itinerary of many destinations.”
- Centrifugal Corridor: “Agglomeration of corridors using different modes of transportation which connect hubs along an axial belt. Integration of infrastructures in production, transformation and consumption of goods.”

Banomyong defines four phases in economic corridor development (Banomyong, 2013):

1. Transport Corridor: “Corridor that physically links an area or region.”
2. Multimodal Transport Corridor: “Corridor that physically links an area or region through the integration of various modes of transport.”
3. Logistics Corridor: “Corridor that not only physically links an area or a region but also harmonizes the corridor’s institutional framework to facilitate the efficient movement and storage of freight, people, and related information.”
4. Economic Corridor: “Corridor that is able to attract investment and generate economic activities along the less developed area or region. Physical linkages and logistics facilitation must first be in place.”

These two frameworks allow for a better categorization of the types of development projects that have already taken place in juxtaposition with the Northern Corridor Concept proposal.

This article's research design can be considered a mixed research design, qualitative and quantitative. It is mostly qualitative due to the case study approach utilized. It also has quantitative components due to the use of geographic software to determine if an infrastructure is considered "northern". A multi-case approach comparing three historical phases to the Northern Corridor Concept was preferred over a two-case design, i.e., one that compares the Northern Corridor Concept to Quebec's history as a whole, because it singles out certain components from the history of infrastructure development in Northern Quebec. For this research design, purposeful sampling was preferred over probability sampling because one of the objectives of this article is to only examine infrastructure that fit certain criterion rather than all infrastructures in Quebec across all time periods.

All the data needed for the comparative case studies analysis was collected from archival sources. Maps of the current electrical, rail and road infrastructures were used to draw a list of existing infrastructures, and coordinates and geographic data were collected on the GéoIndex platform. Specific information pertaining to the list entries were collected through a documentation study of Quebec's Ministry of Transportation's Archives and Hydro-Quebec's public records, consulted at Bibliothèque et Archives nationales du Québec in Montreal.

4.3 Part 2: Nordicity in Quebec

To analyze the different projects that have been proposed to develop Quebec's North, it is important to first define the North as objectively as possible.

The definition of what constitutes Quebec's North has evolved with time. The province of Quebec's geographical delimitations changed in 1898 (Quebec, 1898) with the province's enlargement up to the James Bay, in 1912 (Quebec, 1912) with the addition of present-day Nunavik and in 1927 (Newfoundland, 1927) with the redefinition of the borders of Labrador. These changes also modified the definition of the province's North. Until the start of northern infrastructure development in the second half of the twentieth century, Quebec's North could be loosely defined as the Northern Laurentians, the Abitibi Lowlands, the Lac-Saint-Jean region and anything further septentrional (Duhaime et al., 2013; Simard, 2017a). Nowadays, this definition is largely outdated in determining what truly constitutes the "North", as most of these regions have developed economically and technologically, distancing them semantically from what would be considered the vast uncharted territories more commonly referred to as "Northern Quebec". To define the North in the context of the proposed Northern Corridor Concept, this article will have to use a more contemporary definition.

Simard (2017b) chronologically compares four different ways of defining what constitutes Quebec's North according to four different researchers having studied Quebec nordicity. He examines the different conceptions of the North and compares them to each other, discussing the geographical, sociological and anthropological implications of each perspective. He notes the value of each approach and tries to decipher the intent or ideology behind each one. This article will only take into account the more objective and geographical methods explicated by Simard. These methods will draft a clearer path towards identifying which infrastructures can be considered as genuinely northern with the least ideological bias possible and reliably based on palpable scientific measurements. Simard suggests that Louis-Edmond Hamelin's work (Hamelin, 1968, 1975, 2000), together with Jules Dufour's, (Dufour, 1993, 1996, 2012) is possibly the most pertinent in establishing an objective framework as to what constitutes Quebec's North based on geographical and socio-economical data (Simard, 2017b). This resonates with Graham's findings on the different methods used to delineate Canada's North. She concludes that Hamelin's method remains very useful in delimiting what constitutes the North (Graham, 1990). Furthermore, McNiven and Puderer (2000) use many of the same criteria as Hamelin in their delineation of the Canadian North and Vaguet et al. (2018) judge Hamelin's method to be relevant in delineating the North at a global scale. It is also important to note that Dufour's work mostly builds off of Hamelin's. Given the legacy of Hamelin's method in the existing literature and its loyalty to objective indicators, this article will focus on Hamelin's definition of the North.

Hamelin is a pioneer concerning Quebec's North, and the study of nordicity worldwide. He defines the word "nordicity" in the Canadian context as the polar level of a location in the Northern hemisphere, measurable and evolutive in time (Hamelin, 1975). He also created a tangible and empirical definition for the measure of nordicity. He created an indicator known as "VAPO" or "polar value" that can measure the nordicity of a town or locality by generating a score of 1000, where 0 is "least northern" and 1000 is "most northern". The sum of ten criteria each evaluated on scales of 1 to 100 equals the score on 1000. Six of the ten criteria are strictly geospatial or biophysical (Latitude, Number of summer days, Annual freezing days, Level of permafrost, Levels of precipitation, Vegetation) and four out of ten criteria are socioeconomic (Access by road or boat, Access by plane, Population density, Economic activity) (Hamelin, 1968). Much like a topographic altitude map, Hamelin's VAPO indicators allow for the creation of what he calls "Isonords", or lines on a map delimiting the zones of a given VAPO score. From a score of 200 to 300, he considers the zone to be the "Lower Middle North"; from 300 to 500, the "Upper Middle North"; above 500, the "Great North" (Hamelin, 2000).

Taking into account these criteria, it is evident that his model underlines the evolutive nature of his definition of nordicity (Vaguet et al., 2018). The environmental criteria could change progressively and may change more and more rapidly due to climate change. Still, the socio-economic criteria have the biggest potential for change due to the possibility of a rapid decrease in the criteria from any form of economic development in the concerned regions. This is an important point to underline when qualifying infrastructures as "northern" with this measuring system. According to this scale, the very construction of a proposed northern infrastructure project could lower the nordicity level of the region in which it is built. Economic activity, access (air, road or rail) and population tend to fluctuate positively with the arrival of large infrastructure projects in a region. The VAPO scores would have to be updated periodically for them to stay accurate over time. This would most probably push the limit of the Lower Middle North northbound incrementally, proportionately to the northern infrastructure projects constructed over time. Furthermore, Hamelin's methodology could also serve as a way to empirically track the progress of northern infrastructure development by recalculating the VAPO score for different localities over time. The evolutive aspect of this measurement scale does not inherently discredit this tool as a way to determine where is North and where it isn't, but it is important to keep in mind that what is considered "Northern" today may not be tomorrow.

Nonetheless, for the objectives of this article, Hamelin's scale is currently the most accurate tool to be able to judge if a town or locality is considered northern based on factors that are measurable through obtainable data. The spatial and physical nature of the infrastructures examined in this article justifies the need for a measuring tool that takes into account these qualities. The infrastructures that will be considered as northern in the following parts of this article will be those that cross the 200 VAPO isonord or are fully located above it (Hamelin, 2000). This theoretical border between the North and the South is shown in Figure 4.1.

4.4 Part 3: Existing Transportation Infrastructures in Northern Quebec

The infrastructures that cross the 200 VAPO isonord or are above it are relatively few compared to the totality of infrastructures in Quebec. Previous literature has sought to divide existing infrastructures by northern region or type of infrastructure (Paquet 2001; Brisson, 2014). These categorizations do not take into account the historical background of infrastructure development, as well as the geographical progression of infrastructures into more northern regions. Consequently, the data we collected were used to generate three distinct groupings of infrastructures based on when they were constructed and the objectives set during planning.

The groupings take into account the chronology of infrastructure developments in Northern Quebec as well as the objectives and stakeholders driving these developments. The first grouping includes infrastructures that were built primarily to serve private interests before Hydro-Quebec's rise. Because of the sheer quantity of infrastructure projects, the state enterprise initiated and the circumstantial monopoly the organization had on northern development for many years, Hydro-Quebec can be considered to have played a pivotal role in developing Quebec's Middle North. As such, there is a substantial concentration of infrastructure development in the years marking the crown corporation's expansion. The second grouping includes the infrastructures related to these Hydro-Quebec projects. Northern Quebec infrastructure development experienced a hiatus following the Hydro-Quebec golden age, with no infrastructure projects proposed or brought to fruition between 2001 and 2011, the latter in which the Plan Nord was proposed. The third grouping will comprise of all the infrastructures built following the Plan Nord proposal.

The first group (Table 4.1) encompasses the infrastructures constructed from 1949 to 1963 that were mostly used for the transportation of minerals from the Lower-Middle North to southern Quebec. Private companies were predominantly involved in the construction and operation of the infrastructures, the majority of which were railways.

Table 4.1 : First Group of Infrastructures: Mining in Northern Quebec

Infrastructure Name	Owner	Northern Region of Quebec	Type of Infrastructure	Year of Original Construction	Southernmost Point	Northernmost Point	Length (km)
Romaine River Railway	Rio Tinto, Iron & Titanium Inc.	Côte-Nord	Rail	1949	Havre-Saint-Pierre	Lac-Allard	43
Quebec Route 167	Ministry of Transportation of Quebec	Jamésie	Road	1949	Saint-Félicien	Chibougamau	202
Quebec North Shore and Labrador Railway	From Sept-Îles to Emeril Junction: Iron Ore Company of Canada From Emeril Junction to Schefferville: Tshiuetin Rail Transportation Inc.	Côte-Nord	Rail	1954	Sept-Îles	Schefferville	578
Barraute-Franquet Railway	Canadian National (CN)	Jamésie	Rail	1955	Barraute	Franquet	126
Chapais-Chibougamau Railway	Canadian National (CN)	Jamésie	Rail	1957	Chapais	Chibougamau	37
Saint-Félicien-Chibougamau Railway	Canadian National (CN)	Jamésie	Rail	1959	Saint-Félicien	Chibougamau	229
Port-Cartier-Mount Wright Railway	Arcelormittal Infrastructure Canada SENC	Côte-Nord	Rail	From Port-Cartier to Gagnon: 1960 From Gagnon to Mount Wright: 1977	Port-Cartier	Mount Wright	420
Quebec Route 113	Ministry of Transportation of Quebec	Jamésie	Road	1960	Senneterre	Chibougamau	341
Quebec Route 109	Ministry of Transportation of Quebec	Jamésie	Road	1961	Amos	Matagami	223
Franquet-Matagami Railway	Canadian National (CN)	Jamésie	Rail	1963	Franquet	Matagami	99

The second group (Table 4.2) includes the infrastructures that are related to Hydro-Quebec’s hydroelectric infrastructure projects in the Middle-North from 1953 to 2001. Since Hydro-Quebec is a state-owned company, the infrastructures constructed in this period benefited from a high level of government involvement.

Table 4.2 : Second Group of Infrastructures: Hydro-Quebec

Infrastructure Name	Owner	Northern Region of Quebec	Type of Infrastructure	Year of Original Construction	Southernmost Point	Northernmost Point	Length (km)
Bersimis Complex High Voltage Power Lines	Hydro-Quebec	Côte-Nord	Power Line	1953	Montreal	Bersimis-1 Power Station	≈600
Quebec Route 389	Ministry of Transportation of Quebec	Côte-Nord	Road	1961	Baie-Comeau	Labrador City	567
Churchill Falls High Voltage Power Lines	Hydro-Quebec	Côte-Nord	Power Line	1971	Baie-Comeau	Churchill Falls	412
Manic-Outardes Complex High Voltage Power Lines	Hydro-Quebec	Côte-Nord	Power Line	1971	Quebec City	Manic-5 Power Station	974
James Bay Road	Hydro-Quebec	Jamésie	Road	1974	Matagami	Chisasibi	620
Quebec Route 138	Ministry of Transportation of Quebec	Côte-Nord	Road	1976	Sept-Îles	Havre-Saint-Pierre	218
Transtaïga Road	Hydro-Quebec	Jamésie	Road	1979	Radisson	Caniapiscau Reservoir	666
James Bay Transportation Network (Phase 1)	Hydro-Quebec	Jamésie	Power Line	1984	La Grande Hydroelectric Complex	Montreal	≈1000
Wemindji Road	Ministry of Transportation of Quebec	Jamésie	Road	1992	Wemindji	Junction with James Bay Road	96
North Road	Ministry of Transportation of Quebec	Jamésie	Road	1993	Junction with Quebec Route 167	Junction with James Bay Road	406
Eastmain Road	Ministry of Transportation of Quebec	Jamésie	Road	1994	Junction with James Bay Road	Eastmain	103
Quebec Route 138	Ministry of Transportation of Quebec	Côte-Nord	Road	1996	Havre-Saint-Pierre	Natashquan	151
James Bay Transportation Network (Phase 2)	Hydro-Quebec	Jamésie	Power Line	1996	La Grande Hydroelectric Complex	Montreal	≈1000
Waskaganish Road	Ministry of Transportation of Quebec	Jamésie	Road	2001	Junction with James Bay Road	Waskaganish	102

The third group (Table 4.3) consists of the infrastructures that have been built more recently as part of the Plan Nord development scheme, which was a collaboration between government and private interests. The only determining factor in grouping these infrastructures is their affiliation with the Plan Nord.

Table 4.3 : Third Group of Infrastructures: Plan Nord

Infrastructure Name	Owner	Northern Region of Quebec	Type of Infrastructure	Year of Original Construction	Southernmost Point	Northernmost Point	Length (km)
La Romaine Complex Power Lines	Hydro-Quebec	Côte-Nord	Power Line	2012	Havre-Saint-Pierre	La Romaine Complex	262
Quebec Route 138	Ministry of Transportation of Quebec	Côte-Nord	Road	2013	Nastashquan	Kegashka	40
Quebec Route 167	Ministry of Transportation of Quebec	Jamésie	Road	2013	Témiscamie	Stornoway Renard Diamond Mine	240

Each group of infrastructure entries above will be broached as a historical case study in the following section.

4.5 Part 4: Three Phases in the Development of Northern Quebec

Since the 1950s, government agencies, as well as private interests, have sought to develop resource-rich northern Quebec by planning infrastructure projects that facilitate the extraction of its bountiful natural resources. Minerals and hydroelectricity have been the main drivers of development, requiring the construction of railways, roads and power lines to connect the resource extraction points to the South’s infrastructures.

4.5.1 Phase 1: Mining in Northern Quebec: From Pre-North To Mid-North

Prior to the development of Northern infrastructures as defined in Part 3, regions in periphery of what can be considered the North were colonized, including Lac-Saint-Jean, Abitibi and Côte-Nord. This was accompanied by several infrastructure projects that constituted the first incursions into the Lower Middle North.

The first permanent settlements in the Lac-Saint-Jean region were established in the first half of the 19th century (Girard, 2012). By 1869, the first railway connecting Quebec City to the region was built. In the early 1900s, mining companies and prospectors started evaluating the geological content of the regions beyond the Saint-Jean Lake, notably near Lake Chibougamau, further Northwest. Narrow and rustic "winter roads" were built as early as 1910 to link Saint-Félicien in Lac-Saint-Jean to the Lake Chibougamau region. These roads' main purpose was to cater to the needs of the expansive wood industry. By 1938, several mining companies were exploiting mineral deposits near Chibougamau, but the capacity of the existing transportation infrastructures wasn't sufficient to justify large-scale mining operations. In 1949, the first gravel road connecting Saint-Félicien to Chibougamau was completed to better serve the mining companies with titles in the region. In 1957, the construction of a railway from Barraute in Abitibi to Chibougamau was completed to facilitate the transportation of mined metals to refining plants in Abitibi. Two years later, in 1959, a railway was built to connect Chibougamau to Saint-Félicien, forming a rail loop connecting Abitibi to Lac-Saint-Jean. The portion of the railway between Abitibi and Chibougamau has since closed, but the other portions of the railways mentioned above are still in operation (Girard, 2012).

In Abitibi, modern infrastructure developments date back to the beginning of the 20th Century. Following the redefinition of Quebec's borders in 1898 (Quebec, 1898), Abitibi went through several waves of colonization driven by the provincial government's economic policies. Due to its dense forests and rich gold deposits, the region experienced an industrial boom that incited the creation of towns along the Cadillac fault. The Transcontinental Railway, finished in 1913, was the first to connect Montreal to the Abitibi region. The Quebec Government's 1934 Vautrin Plan, named after the then-Minister of Colonization Irénée Vautrin, intensified colonization efforts and generated population growth in the region. At the time, the Ministry of Colonization was mandated with making land suitable for agriculture. In the context of the Great Depression, there was a strong back-to-the-land movement, which renewed this Ministry's importance. Jobs were plentiful in rural areas and city-dwellers left urban centers for Abitibi with the promise of newfound wealth. By the 1950s, mining promoters in the region wanted to develop regions further North, aware of substantial mineral deposits near the present-day town of Matagami. The road connecting Matagami to Amos, one of the cities bordering the Transcontinental Railway, was completed in 1961. The town was also connected by railway to the rest of Canadian National's network in 1963 by a diversion at the Franquet junction on the Barraute-Chibougamau railway (Gourd, 2007). The infrastructure projects to Matagami and Chibougamau mark the beginning of infrastructure development in the James Bay region, also known as "Jamésie" in French.

The Côte-Nord region's economy was mostly driven by commercial fishing until the 1920s when the pulp and papers industry developed coastal fishing villages such as Baie-Comeau or Sept-Îles into small industrialized cities. Most of the economic activity was concentrated around the coast. The mineral-rich Labrador fault, for which the southernmost point is located in the Northern part of the Côte-Nord region, was mostly unexploited and uninhabited. In 1948, Quebec Iron and Titanium started investing in a mine north of Havre-Saint-Pierre. A year later, in 1949, a 43-kilometre railway was built to connect the mine to the town on the riverside of La Romaine River. In 1950, the construction of an ambitious project, a railway that would connect the coast to mines in Labrador, commenced. The 578 kilometres of tracks through treacherous terrain and polar weather dragged the construction of the railway over four years. In 1954, the railway known as the Quebec North Shore and Labrador Railway was completed, connecting Sept-Îles with Schefferville, a mining town founded the same year, located on the border of Quebec and Northern Labrador. In 1960, a third railway was built, stretching from Port-Cartier on the coast to the town of Gagnonville (Leclerc, 1987). All three railways were built to bring iron ore from the North to the sea and are still in operation today. The port installations of the maritime access points that act as the Southern ends of the railways developed infrastructures to process and load the iron ore onto ships, creating jobs and economic activity.

The totality of the infrastructures developed for mining was meant to connect the more densely populated South to the resource-rich North. Most of the transportation infrastructures mentioned above are directly or indirectly linked to growth in Quebec's mining sector following the Second World War. While being an important phase of infrastructure development, there was no cohesive plan by the government or a single private interest in this phase of infrastructure development. Each infrastructure project was more or less standalone, with singular objectives specific to the infrastructure being built. Private companies had infrastructures built to service the demands of extraction sites in the Lower Middle North. Northern Quebec's plentiful mineral resources undoubtedly played an important role in the territory's early infrastructure development.

Railways characterize this era of northern resource exploitation. They are the remnants of the railway's glory days in the first half of the 20th century, but are still ubiquitously used for mining applications in Northern Quebec to this day. Quebec's first phase of northern development could be characterized as a period of extractivism. Extractivism is defined as removing natural resources in large quantities before transformation, usually to be exported. (Acosta, 2013) While many of the extracted resources transported by railways financed by the mining companies were meant for use in southern Quebec, they weren't processed or transformed in northern regions. The extractivism practiced in Northern Quebec, while offering the provincial mining industry a competitive advantage by enhancing means of transportation and economies of scale, has not always yielded perennial benefits for northern communities. Many mining towns established with the construction of these railways experienced severe economic downturn following the closing of each's nearby mine. A good example of this phenomenon is the case of Gagnonville in Côte-Nord: once a booming mining town attracting inhabitants and investments, now a deserted ghost town barely on the map. The infrastructure planning in this phase of development was profit-driven and sought out financial opportunities from the North in the short-term, with no other real goal but to access the resources as efficiently and cheaply as possible (Duhaime et al., 2013).

4.5.2 Phase 2: Hydro-Quebec: Up the Middle North's Rivers

Hydro-Quebec, the state-owned electricity utility of the Government of Quebec, was instrumental in developing northern Quebec's infrastructures. Hydro-Quebec's rapid expansion in the 1960s and its large dams are a symbol of Quebec nationalism and the economic growth of the province. Many of the rivers that are used to produce electricity are located in remote regions of northern Quebec. The grand-scale production of electricity by way of hydroelectric dams required the construction of service roads and high-voltage electrical lines to connect the dams with Southern Quebec, where most of the electricity is consumed. The crown corporation's projects in the James Bay region and the upper Côte-Nord region helped build a big part of the northern infrastructures that are in use today.

The Bersimis-1 and Bersimis-2 hydroelectric generating stations were built in 1953 and 1959 along the Betsiamites River in the Lower Côte-Nord region (Bélanger and Comeau, 1995). While both stations are not quite located in what Hamelin considers to be the Lower Middle North, the Betsiamites River project was different from previous generating station projects in that the facilities were to be built over 600 kilometres away from Montreal in a mostly inaccessible region. The electrical lines linking the stations to Montreal were a substantial challenge for Hydro-Quebec's engineers. To lose the least amount of energy possible and construct fewer lines over such distances, it was desirable for the cables to be serviced with a very high voltage. Jean-Jacques Archambault, a young engineer working for Hydro-Quebec at the time, convinced senior engineers that the power lines could be run at 315kV rather than the era's standard of 120kV. In 1960, he developed the technology to run power lines at 735kV. (Archambault, 1984) Such advancements in energy transportation gave Hydro-Quebec the confidence to propose projects further North, thus paving the way for the development of Northern infrastructures.

The 1960s marked the start of Hydro-Quebec's venture into Quebec's North. The Manic-Outardes project, for which the planning started in 1955, set out to utilize the hydroelectric potential of the Manicouagan and Outardes rivers in the Côte-Nord region. A total of seven power stations were built from 1964 to 1978, the largest and northernmost being the Daniel-Johnson Dam and power station in 1964 (Bolduc et al., 1979). Three power lines each spanning 974 kilometres at a voltage of 735kV were built to connect the power stations to Montreal. Archambault's technology proved itself to be efficient to transport electricity over such distances (Paradis, 1967). In 1969, Hydro-Quebec agreed to buy the electricity generated from the Churchill Falls generating station located in Labrador. This station was one of the biggest hydroelectric projects of its time, financed in part by the Newfoundland government, the Rothschilds and other prominent British financiers (Bolduc et al., 1979). To honour the agreement, the public utility built three 735kV connecting the station in Labrador to the southernly coastal power lines in 1971 (Coté, 1972).

While the Manic-Outardes and Churchill Falls projects were able to supply electricity to Quebec's inhabitants in 1970, Hydro-Quebec was predicting that by 1980 their output wouldn't be sufficient. The government was at a crossroads: it needed to decide if more hydroelectricity projects were a better option than increasingly efficient nuclear energy production (Bolduc, 2000). In 1972, after evaluating the hydroelectric potential of many bodies of water in northern Quebec, the Government of Quebec decided to build generating stations along La Grande River in the James Bay region (Bolduc et al., 1979). This is the start of what was named the “James Bay Project”. The La Grande River infrastructure developments outlined in 1972 would be later known as Phase 1 of the James Bay Project. A narrow temporary service road was first constructed connecting the town of Matagami to the mouth of the La Grande River to kickstart the construction of the hydroelectric complex. The permanent road, known as the James Bay Road, was completed two years later in 1974. In 1979, a second road, known as the Transtaïga Road, was built from the mouth of La Grande River to the Caniapiscau reservoir 554 kilometres East. From 1973 to 1984, three power generating stations were built along La Grande River. To connect these stations to Montreal and Quebec City, five 735kV power lines were built spanning over 1000 kilometres each (SEBJ, 1987).

Phase 2 of the James Bay Project commenced in 1988 and consisted of the construction of two new power generation stations on La Grande River as well as adding two more power lines to connect the generating stations to the South, finally completed in 1996 (SEBJ, 1996). Roads connecting the small coastal towns of the James Bay to the James Bay Road were built from 1992 to 2001. Meanwhile, the government announced more generating stations were going to be built on the Grande Rivière de la Baleine, Petite Rivière de la Baleine and the Coast River, located in Nunavik, North of La Grande River. This project was known as the Grande-Baleine Project. However, after a series of conflicts with the local Cree community, the project was cancelled (Dufour, 1996). It would have been the first major infrastructure project in the Nunavik region, and the northernmost hydroelectric project in Quebec to this day.

Hydro-Quebec’s vast hydroelectric projects contributed to developing roads and power lines in northern Quebec. The communities on the coast of the James Bay would have otherwise been isolated from any road access. Harnessing the hydroelectric capacity of Quebec’s mighty rivers assuredly incentivized the development of Quebec’s North.

Hydro-Quebec’s objective was to help the province gain autonomy through a plan of nationalization of natural resources. The sheer size of the projects constructed in the North became a symbol of Quebec’s success following the Quiet Revolution. To this day, the celebration of this success is still a part of the province’s collective consciousness and identity (Perron, 2003). Hydro-

Quebec's role in Quebec's society is larger than only being a state-run utility. The James Bay Project has had a lasting impact on the way southern inhabitants of Quebec view Northern Quebec. The projects the corporation undertook shaped the common thinking of Quebeckers and forced Quebec to take stock of certain issues head-on such as indigenous issues (Savard, 2009). Cooperation with indigenous communities in the James Bay Region wasn't easy throughout this phase of development, but it was nonetheless improved, culminating in "The Peace of the Braves" (Paix des Braves) agreement in 2002 between Cree nations and the Quebec Government. The agreement ensured that revenues from forestry, mining and hydroelectricity were shared equally with inhabitants of the Cree lands from which resources were exploited (Paix des Braves, 2002).

4.5.3 Phase 3: Plan Nord: Unfinished Business

The end of the 1990s saw a slowdown of important Northern infrastructure developments in Quebec. To this day, no infrastructure projects of the magnitude of Hydro-Quebec's James Bay Project have been completed. The cancellation of the Grande-Baleine Project and greater concern for the territorial rights of indigenous communities made the planning of infrastructure projects in the North slightly more contentious and politically hazardous (Brun et al., 2017).

Nonetheless, the question of transportation infrastructure to connect the Nunavik region to the south was seen as the next frontier of Quebec's northern development. Nunavik is the portion of Quebec traditionally inhabited by the Inuit North of the 55th parallel and spans part of the Upper Middle North and the Great North. The Great North had yet to become accessible. Nunavik's remoteness and low population density made it difficult to justify the construction of infrastructures. However, in 1997, the Ministry of Transportation of Quebec mandated a group of its experts to evaluate the feasibility of a road or rail link connecting the town of Kuujjuaq near the Ungava Bay to the rest of Quebec's infrastructure network. The study proposed two different routes: 1) Schefferville to Kuujjuaq and 2) Caniapiscau, the end tip of the Transtaïga Road, to Kuujjuaq. The authors of the study preferred the Schefferville option to the Caniapiscau option, even if the latter would be less expensive to build (MTQ, 1997). Ultimately, the study didn't lead to the construction of a road or railway, and no projects connecting Kuujjuaq to the South were initiated.

In 2011, the Government of Quebec announced a large-scale northern economic and social development plan. The Plan Nord earmarked 80 billion dollars in public and private funds to develop a multitude of projects as well as predicting the creation of 20 000 new jobs in northern Quebec (CBC, 2011). The projects proposed were far-ranging: transportation infrastructure projects, mining partnerships with private firms, hydroelectric projects with Hydro-Quebec. The Plan Nord was touted as a comprehensive development project of the North, creating jobs for indigenous communities and generating overwhelmingly positive and perennial economic activity to localities that had experienced economic hardship. Private companies were meant to invest in infrastructure projects that would create economic activity as well as make remote parts of northern Quebec accessible. Of the transportation infrastructure projects proposed in the Plan Nord's documentation, the following projects are those that suggested the construction of new infrastructures (Brisson, 2014):

- Prolonging Quebec Route 138 in Côte-Nord from Natashquan to Blanc-Sablon.
- Prolonging the James Bay Road from Radisson to Kuujjuarapik in Nunavik.
- Prolonging Quebec Route 167 from Témiscamie to join the Transtaïga Road.
- Constructing power lines leading to the Romaine hydroelectric power stations.
- Prolonging the Quebec North Shore and Labrador Railway from Schefferville to Kuujjuaq.

Some of these projects were put into action, others weren't. Route 138 was prolonged in 2013 to Kegashka. Currently, construction for the portion linking Kegashka to La Romaine is underway, and feasibility studies to evaluate the costs of a road to Blanc-Sablon are being done (Plan Nord, 2017). The project to prolong the James Bay Road was axed from the Plan Nord's infrastructure priorities and is not planned any time soon (Plan Nord, 2015). Route 167 was extended to the Stornoway Renard Diamond Mine in 2013, but connecting the mine to the Transtaïga Road is no longer on the table. Power lines connecting the Romaine generating stations were built in 2013 by Hydro-Quebec. The railway expansion to Kuujjuaq was subject to a pre-feasibility study in 2011 (GENIVAR, 2011) before being subsequently abandoned.

The Plan Nord was supposed to be a great leap forward in Quebec's northern development. By 2015, the public's expectations were already much lower than those of 2011 and the plan's objectives were less ambitious. Many mining companies that had spoken of investing in projects included in the Plan Nord had pulled out of the development plan before 2015 because of crashing commodity prices on the global markets. The infrastructure projects that were supposed to rejuvenate and develop remote communities were more or less abandoned due to lack of interest (Brun et al., 2017). Ultimately, the only infrastructure projects that were built were ones that were already planned prior to 2011, those of Hydro-Quebec and Route 138, as well as the prolongation of Route 167, built essentially to serve a private company's diamond mine. The Plan Nord could hardly be considered a comprehensive northern development plan.

4.6 Part 5: The Canadian Northern Corridor's Proposed Quebec Portion

In 2016, the University of Calgary's Policy School researchers Andrei Sulzenko and Kent Fellows published an article outlining a proposal for what they call the "Northern Corridor Concept" (Sulzenko and Fellows, 2016). This article and a subsequent article specifying this proposal (Fellows et al., 2020) compare the project to previous projects that cross the whole country. In the past, the federal government of Canada has fostered large-scale transportation infrastructure projects connecting different provinces, such as the Canadian National Railway, the Canadian Pacific Railway, the St-Lawrence Seaway and the Trans-Canada Highway. These four projects have all depended on the cooperation of provinces including that of Quebec. Since the late 1960s, there has been little interest in constructing Pan-Canadian infrastructures, with most large infrastructure projects in Canada being organized at the provincial or municipal level (Fellows et al., 2020). While enthusiasm for Pan-Canadian projects may have diminished, enthusiasm for large infrastructure projects in general continued. Quebec's northern infrastructure boom in the 1960s, 1970s and 1980s, in part caused by Hydro-Québec's success, is a direct result of this continued enthusiasm. Because of how monumental a development program of the likes of the Northern Corridor Concept is, it would become in of itself a completely new phase of infrastructure development in Northern Quebec. To better identify the implications of this proposal, it is important to understand what it suggests in terms of Quebec's northern development.

Fellows et al. (2020) drew a rough outline of what the corridor would look like on a map. The outline for the corridor utilizes existing infrastructures to conceive an infrastructure framework that would cover many unserved regions of Canada while connecting transport hubs and junctions to sea access. As shown in Figure 4.2, the rough outline connects Northern Ontario to what can be made out as Matagami in Jamésie. The corridor then runs northbound to a remote point in the Nord-du-Québec administrative region that could best be described as the extremity of the Manicouagan Reservoir. At this point, the corridor splits into two lanes, one culminating in Blanc-Sablon at the Labrador and Quebec border and the other at Sept-Îles in Côte-Nord. both lanes allow for the northern corridor to connect to the St-Lawrence Seaway and the Atlantic Ocean. It is interesting to note that the outline of the Northern Corridor as proposed in the Fellows et al.'s article (2020) shown in Figure 4.2 closely resembles the delimitation of the North and South in Figure 4.1. The proposal connects several towns that are located directly above or below this delimitation and that are commonly seen as "gateways" to the North, such as Matagami, Chibougamau or Sept-Îles. This indicates that the Northern Corridor is less of a vehicle to reach new remote locations in Northern Quebec, but rather of a new way for locations that are already connected to the southern road network to communicate with each other.

If one of the objectives of the Northern Corridor is to make use of existing infrastructures in Northern Quebec (Sulzenko and Fellows, 2016), new roads connecting existing roads or railways would likely be the most plausible and least costly way to roughly attain Fellows et al.'s (2020) outline. Three distinct opportunities for the Quebec segment of the Northern Corridor Concept could constitute potential options for the project's stakeholders. These options are shown in Figure 4.3 (grey denotes existing infrastructure corridors). The first option, as proposed by the Ministère des Transports du Québec (1997), is that of connecting Caniapiscau to Schefferville and Schefferville to Kuujjuaq by prolonging the Transtaïga road (extension marked in blue). The second option would be to extend route 167 beyond the Stornoway Diamond Mine, all the way to Fermont, connecting it to Labrador's highway network (extension marked in yellow). The third option (in red) is a corridor that closely follows the border between the North and the South as shown in Figure 4.1. This corridor would essentially reuse existing infrastructures connecting Abitibi to Lac-Saint-Jean, Lac-Saint-Jean to Port-Cartier and Port-Cartier to Fermont. Rather than build new roads, Option 3 would seek to augment the capacity of existing roads and would possibly increase the performance of the new corridor. All three options feature a connection with Labrador. The second option would be the closest to the Northern Corridor outlined by Fellows et al. (2020), while the first option is the least in line with it. The first option offers a connection to Nunavik, a region that currently has no road infrastructure, while the second and third options are more focused on East-West connection. The objectives of the corridor would have to be clearly defined to be able to choose between these three options.

4.7 Part 6: Discussion

Quebec's northern development history is almost exclusively based on the notion that there is a plethora of resources to be extracted and brought to the South for transformation and commerce. Each phase of Quebec's northern development sought to create penetration corridors, as defined in Comtois' classification (2012). All of the infrastructures built or planned during the three phases of northern infrastructure development in Quebec were meant to connect the peripheral regions of southern Quebec to the resource-rich northern regions to transport the resources for consumption or transformation in the south (Proulx, 2014). In Banomyong's classification of corridors (2013), the three phases would be considered transport corridors. While the Hydro-Quebec and Plan Nord phases opt for multimodal options within its proposed corridors, the exploratory nature of the projects involved does not allow the corridors created to graduate to the rank of logistics corridor or economic corridor.

4.7.1 The Northern Corridor Concept: A new type of corridor in Québec's Middle North

The Canadian Northern Corridor Concept seeks to attain many different objectives (Fellows et al., 2020): Improving economic outcomes for the country, improving standards of living in Northern Canada, streamlining environmental protection, safeguarding indigenous agency and promoting Canada's global and strategic significance. These objectives would mostly be achieved by way of country-wide integration of northern transportation networks to maximize the economic impact of infrastructure investments while reducing the negative environmental and social externalities.

However, given the magnitude of the investments needs and the trade growth sought after, the principal objective of the Canadian Northern Corridor is the pursuit of economic growth for the country as a whole. The rationale for the corridor is largely driven from the gains to be made in the extraction and trade of natural resources, still accounting for roughly 20% of Canada's GDP. Canada still has important infrastructure bottlenecks, namely overcrowded ports in big cities and too few reliable roads in remote areas (Rodrigue, 2021). To this day, the extraction of resources in remote areas and international trading of those resources remain costly and logistically complicated due to the lack of infrastructure in northern Canada. Landlocked resource-rich provinces could export their resources to coastal provinces to access the international market. However, apart from an increase in trade, it is not clear that Quebec stands to directly benefit from such an arrangement, as the province already has access to the Saint-Lawrence seaway to efficiently export resources.

Table 4.4 shows Northern Quebec's three phases of development compared against the Northern Corridor Concept. The Northern Corridor Concept is meant to create a different type of corridor. In Comtois' classification (2012), the Northern Corridor would be more akin to a "chain corridor". The Northern Corridor Concept seeks to promote trade between provinces (Sulzenko and Fellows, 2016). This is different from the penetration corridors previously employed in Northern Quebec, where the interprovincial trade component was inexistent, and the idea of many locations connected to each other to form a network was secondary.

According to Banomyong's classification (2013), the Northern Corridor as currently described is an economic corridor. Whether this is a realistic expectation is questionable, but what is clear is that the Northern Corridor Concept espouses an ideal of national economic development, rejuvenating small towns through the attraction of investments, connecting rural areas to Canada's greater transportation network. This is arguably also very different from Quebec's previous northern development plans, which promoted extractivism and did very little to create perennial and economically developed communities.

Table 4.4 : Comparison of Historical Periods of Northern Infrastructure Development in Quebec with the Northern Corridor Concept

Case	Time Period	Type of Corridor Proposed (Comtois Classification)	Type of Corridor Proposed (Banomyong Classification)	Modes of Transportation Planned	Type of Financing
Mining in Northern Quebec	1949-1963	Penetration Corridor	Transport Corridor	Railways, Roads	Private
Hydro-Quebec	1953-2001	Penetration Corridor	Multimodal Transport Corridor	Roads, Power Lines	Public
Plan Nord	2011-present	Penetration Corridor	Multimodal Transport Corridor	Roads, Power Lines, Railways	Public/Private
Northern Corridor Concept	N/A	Chain Corridor	Economic Corridor	Roads, Power Lines, Railways, Pipelines	Public/Private

4.7.2 The Northern Corridor Concept in Québec: A complex undertaking

The introduction of a new type of corridor in northern Quebec could be beneficial, considering enhanced trade with the rest of Canada and the development of the rural areas the corridor would cross. In this sense, the Northern Corridor Concept captures an opportunity and sets out to do something that has never been done in the province. Exporting hydroelectricity to Ontario and connecting the existing penetration corridors transversally have merit. However, Quebec's history of choosing resource-extraction corridors for northern Quebec may be a testament to the complexity in undertaking projects such as the Northern Corridor Concept.

4.7.2.1 Limited possibility to exploit existing infrastructures

Existing infrastructures in northern Quebec can difficultly be put to use in the conception of a Northern Corridor Concept in respect to the Fellows et al. (2020) outline. A way to limit costs is to build off what has already been built. This could allow for the corridor to become functional quickly, as well as being able to connect existing towns and economic centers to the new infrastructure project. The proposed route cuts across Quebec from West to East, almost perpendicularly to existing infrastructures. This isn’t so much bad planning as an illustration of the reality of Quebec’s existing infrastructures, which more or less follow a North-South axis. Any corridor to Nunavik would be extremely costly, and would keep following a North-South axis while also making a sizeable detour using the Transtaïga road. If anything, the two corridors that could accommodate the trans provincial ambitions of the Northern Corridor Concept are that of Route 167 connecting to Fermont (Option 2 in Figure 4.3) and the pre-existing infrastructures connecting the St-Lawrence Seaway to Labrador (Option 3 in Figure 4.3). The former would still require huge investments to make a sub-optimally long road functional while the latter forces the Northern Corridor to dip south to reach the St-Lawrence Seaway. This would mean that the proposed corridor would either have to go forth with the construction of a new road through completely uncharted territories at a hefty price tag or a corridor that wouldn’t be “northern” the whole way. Both Comtois’ and Banomyong’s classifications outline a gradation of interconnection and economic involvement leading to a type of high-intensity corridor. Proposing a full-blown economic corridor with little consideration for the directionality and geographic reality of existing corridors bypasses these steps and puts any economic corridor project in peril.

4.7.2.2 Challenges to political acceptability

Firstly, the corridor concept’s socio-economic goals are possibly more in line with the provincial government’s recent objectives. A better quality of life for northern communities and respect and reconciliation in regards to the indigenous peoples of Quebec are part of the current provincial government’s Grande Alliance plan (Government of Quebec, 2020). Construction of infrastructures to connect remote areas to more populated centers has been shown to reduce poverty rates (Fan and Chan-Kang, 2005; Khandker et al., 2009) and improve access to schooling, healthcare (Asher and Novosad, 2018) and employment (Olsson, 2009). In that respect, the Northern Corridor Concept has the potential to achieve its quality-of-life goal. It is less clear how successful the NCC will be in safeguarding Indigenous agency. While not a proposal for the construction of specific infrastructures at specific locations, the Northern Corridor Concept proposal describes the constitution of a right-of-way in a pre-determined geographical corridor in northern Canada. Federal and provincial governments would create an environment to facilitate private infrastructure investments within the corridor, thus mitigating risks associated with large-scale projects and lowering the barriers for subsequent investment (Sulzenko and Fellows, 2016). While a proper governance framework has yet to be established, Sulzenko and Koch (2020) have explored the different policy framework options that could be put to use. Within the proposed frameworks, the decision on a precise corridor route and the review of a route proposal are unquestionable steps in the process. The consultation of indigenous peoples would most likely fit itself into these steps. Wright (2020) eloquently argues that the vagueness of the Northern Corridor Concept as to which types of infrastructures at which locations would present a serious issue in the consultation of the indigenous communities whose treaty lands would be affected. For the government to meaningfully consult a community regarding a project, the consultation has to touch upon a specific proposed activity in a specific context. The fact that the corridor concept remains an abstract concept for which it is difficult to predict exactly what infrastructures would be built makes productive consultations problematic. Wright's analysis is especially relevant to Quebec, where there are 6 distinct indigenous nations spanning over a vast territory. During consultations for the Plan Nord, only 4 of those 6 nations were consulted. A divide and conquer strategy was adopted by the provincial government, pinning communities within nations against each other to advance its political agenda. Roads were built in northern regions, but the resulting infrastructure construction was arguably more for the benefit of mining companies rather than the proximal indigenous communities (Asselin, 2011). Consultations for the Northern Corridor would have to be more inclusive and less focused on partner corporations of mining projects.

Secondly, for the corridor's environmental components, much has yet to be researched. Rodrigue (2021) has examined the challenges the environment presents to transport grids in the context of the Canadian Northern Corridor. Pearce et al. (2020) have cited the impacts of climate change on the construction, operation and maintenance of the corridor. Sulzenko and Koch (2020) have underlined the importance of environmental impact assessments in the governance policy framework of the corridor. However, no such assessment has yet been completed. The rationale highlighted by Fellows et al. (2020) is one of limiting environmental damage by focalizing the infrastructure development along a limited surface area across great distances. The lack of literature pertaining to environmental impacts of the corridor is a problem, especially in the Quebec context, where public acceptance of new large-scale projects is largely dependant on sustainability and eco-friendliness.

Lastly, Canadian federalism isn't always a political stance that gets a lot of traction in Quebec. Hydro-Quebec's projects are widely regarded as a first step in the emancipation of the province as well as the most popular accomplishments of those outlined in Part 4 of this article. French-speaking Quebeckers, once economically downtrodden, attribute a part of the economic success of the province to state involvement in natural resource extraction. The Hydro-Quebec phase of northern development also coincided with two referendums to gain autonomy from the centralized federal government or separate unilaterally from Canada. Since then, any form of involvement on the part of Canada's federal government in the province's affairs is subject to additional scrutiny. All three previous phases of development in Quebec sought to attain provincial objectives rather than federal ones. It is safe to say that the Northern Corridor Concept is enmeshed in a vision of interprovincial cooperation. It is not unimaginable that a federally-funded economic corridor seeking to exploit northern Quebec and sell Western provinces' resources through Quebec's ports could be perceived as a form of erosion of Quebec's autonomy.

4.7.2.3 Financing hurdles

The mode of financing proposed in the Northern Corridor Concept has somewhat of a bad track record in Quebec. A framework for private financing with some public financing was an ingredient to the recipe for certain of the Plan Nord's shortcomings. The moment mining companies saw their potential earning crumble through changes in the global commodity market, the provincial government was caught funding the ongoing infrastructure projects, and was no longer able to fully deliver on its socio-economic objectives. The unrealized opportunity of the Plan Nord in regards to losses incurred by changing commodity prices is a testament to the importance of economic diversity. The northern setting is characterized by a few industries that have a high level of economic dependence on global demand of natural resources. In turn, the lack of economic diversity in northern regions fragilizes northern infrastructure projects and puts undue pressure on stakeholders involved. If risk is not properly distributed between stakeholders or codified prior to the start of the project, project failure is a possibility. The situation as experienced by the Plan Nord developers could certainly reproduce itself in a manifold project involving several public and private interests in a dozen Canadian provinces and territories such as the Northern Corridor Concept. As exposed in Part 4, penetration corridors with objectives of resource extraction in Quebec seem to have fared better with single stakeholders and clear ambitions. Promoters of remote and extractive corridors in Quebec should be cautious when opting for private/public models of financing. Caution and better risk allocation are inevitably conducive to reaching the Northern Corridor Concept's main objectives.

4.8 Conclusion

This study compares the Canadian Northern Corridor Concept to the history of northern infrastructure development in Quebec. No specific information pertaining to Quebec's northern infrastructure development in relation to the Northern Corridor Concept has previously been published. Quebec is the second most populous province of Canada, is the largest one by area and is one of the two only provinces to have an arctic region. Understanding how the Northern Corridor Concept contrasts with the previous corridor developments in Northern Quebec is essential in evaluating the feasibility of the corridor in a Pan-Canadian context. Previous literature had not addressed this historical comparison in any way. Examining the way past corridor developments and the corridor that is currently proposed intersect - literally and figuratively - offers necessary information for provincial northern development government stakeholders. Further, this study defines what a "northern infrastructure" is in the Northern Canadian context, which had not previously been done. It comprehensively traces back the history of infrastructure development in Northern Quebec. It outlines a novel intuitive framework to categorize the phases of infrastructure development in Northern Quebec, which is not only useful to stakeholders in the Canadian Northern Corridor project, but also to scholars of many disciplines who will undoubtedly study the region's development over the next decades as Northern Canada opens up to trade. Finally, this study proposes route options that can make use of existing infrastructures in Northern Quebec.

This article makes an important contribution to the shallow body of literature pertaining to the future of Quebec's northern infrastructure development. While not approving or disapproving of the idea of a Northern Corridor, this study demonstrates that the Northern Corridor Concept differs from previous phases of northern development in the province. Financing, geography and political climate remain important challenges ahead and will assuredly influence the project's outcome. During the last century, northern development in Quebec has mutated from extractivism in the Lower Middle North to state-run renewable energy development plans to failed private/public infrastructure development partnerships. The Northern Corridor Concept may or may not be the next installment of Quebec's northern development. The three options presented in this study map out the opportunities available for this installment.

As the Northern Corridor Concept becomes clearer with growing input from its stakeholders, the solutions to the challenges presented by Quebec's unique northern infrastructure development context will become discoverable. For the time being, researchers must focus on the conciliation of Quebec's existing infrastructures with those proposed by the Northern Corridor Concept. Any concrete proposition for infrastructure development in northern Quebec must take into account the political history of the province and the motivations behind previous infrastructure developments. This political history includes the relationship between Quebec and Canadian federalism, which has driven Pan-Canadian infrastructure development in the past. Environmental impact studies must be conducted to ensure the ecological integrity of Quebec's pulchritudinous wilderness. Finally, indigenous communities whose lands would be affected by the construction of infrastructures resulting from the Northern Corridor Concept have to be thoroughly consulted and given the chance to participate in all stages of the development project.

CHAPITRE 5 ARTICLE 2: NORTHERN ROADS AND ECONOMIC DEVELOPMENT

T. Stringer et M. Joanis ont écrit cet article. Celui-ci a été soumis en 2021 à la revue T*ransport Policy*.

5.1 Introduction

The impact of infrastructure development on the economic growth of a country has been subject to a wide breadth of research. Whether it be a reduction of social inequality (Calderón and Servén, 2004), higher wages (Donaldson, 2018; Fingleton and Szumilo, 2019), ease in exporting goods (Ng et al., 2019), firm growth (Barzin et al., 2018), population changes (Iacono and Levinson, 2016) or possible changes in productivity (Aschauer, 1989; Gramlich, 1994; Chandra and Thompson, 2000; Harchaoui and Tarkhani, 2003; Sahoo and Dash, 2009, 2012; Sahoo et al., 2010; Konno et al., 2021), existing literature tends to show significant effects of infrastructure construction on economic development. Road connection, and more specifically rural road access, has been shown to generate tangible benefits for newly connected communities by reducing poverty rates (Fan and Chan-Kang, 2005, 2008; Khandker et al., 2009), improving local employment opportunities (Olsson, 2009), bettering accessibility of remote communities to schooling and healthcare (Asher and Novosad, 2018) and catalyzing the economic competitiveness of connected regions (Démurger, 2001). However, constructing roads to connect remote areas to more populated centers can be very costly (Asher and Novosad, 2018) as well as having the potential to forever change the social and cultural fabric of the communities affected (Cheers, 1993; Chung, 1988). For these reasons, constructing a road connecting a previously isolated community to the main road network can become a bone of contention amongst its inhabitants. Thus, governments and policymakers that are envisaging constructing roads need to understand exactly what these communities stand to gain when sacrificing certain aspects of their way of life.

Arctic and subarctic communities that are geographically remote and that are located in harsh climates can have a higher cost of living, which often affects their poverty rate and quality of life (Daley et al., 2015). The cost of living is more expensive in these communities when they are not connected by road (Nunavut, 2012), which means that road construction could be especially beneficial to them in reducing poverty. Little to no literature specifically touches upon the economic impact of road construction on communities in subarctic or arctic regions. Considering the growing importance of the Arctic in international geopolitics and trade, road construction may very well become a crucial part of any country's plan to access tide-water access points in the Arctic Ocean. Assessing the benefits associated with building roads is the first step towards any further project to be undertaken.

Canada is one of the few countries in the world that can boast a highly prosperous economy while having the vast majority of its nordic landmass uninhabited and undeveloped infrastructure-wise. Northern Canada is the part of the country that has experienced the least amount of infrastructure development, with many towns and villages still disconnected from Southern Canada's road network. Recently, various proposals of road connections to remote localities, such as the Northern Corridor Concept (Sulzenko and Fellows, 2016), the Yukon Resource Gateway Project (Yukon Gateway, 2016) or La Grande Alliance (Dutrisac, 2020), have been floated by different levels of government and think tanks. Each proposal includes the construction of land transport infrastructures to connect previously isolated communities to the country's main road network, purporting this will improve their living conditions and economic opportunities. Each proposal also includes natural resource extraction projects in varying detail. The Quebec-Labrador Peninsula in particular has had a complex history of infrastructure development in its northern region, leading to differing views on whether infrastructure growth is positive for the inhabitants of these regions (Stringer and Joanis, in press).

As mentioned above, existing research suggests that education, labour and income indicators react positively to a new road connection. According to historical data, what has been the effect of road connection on isolated arctic and subarctic communities? Which indicators of socioeconomic development see the biggest increases or decreases after the construction of a road? What can explain these outcomes?

This paper uses census data from Northern Quebec and Labrador to assess the effects of road connection on municipalities connected between 1986 and 2016. Using a difference-in-differences regression model, we find that road connection is correlated with increased employment rates and educational attainment and decreased unemployment rates. These results are robust to the inclusion of fixed effects, covariates and Driscoll-Kraay standard errors. While we also find positive and significant correlations between road connection and income in many specifications, that particular result is not robust when ensuring that error terms are not subject to cross-sectional dependence.

The rest of this paper is structured as follows. Section 2 outlines the empirical model, while Section 3 presents the data with descriptive statistics. Section 4 presents the study's main findings and discusses the possible causes and implications of the effects of road construction observed. The final section offers concluding remarks.

5.2 Empirical Model

We apply a difference-in-differences (DID) approach to quantify the benefits of road construction on remote communities. We focus on community-level outcome measures ranging from average individual income and the labour market to education and demography.

The basic DID model allows for two time periods and two groups, where one group is treated and one isn't, and where both groups follow parallel trends until the treatment occurs (Wing et al., 2018). However, the basic model does not suit many applications, including the application examined in this study, where many groups are treated at different periods over the course of 30 years. Several studies have taken different approaches to modify the basic DID model for more complex applications (Bitler and Carpenter, 2016; Harper et al., 2012; Joanis, 2011; Mark Anderson et al., 2015), notably by using regression models that register year fixed-effects specific to trends between time periods and municipality fixed-effects specific to trends within cross-sectional units.

The basic DID model is modified here to accommodate multiple time periods and multiple groups, considering each census year as a time period, and each municipality as a group. The construction of a road connecting municipalities to the southern ecumene of Canada is interpreted as the "treatment". Control variables are added to account for possible confounders. A dummy variable denoting if treatment has occurred for a specific time period and municipality was also added to the model.

The following fixed-effects model is used for estimation purposes:

$$(1)\ Y_{mt} = \beta_0 + \beta_1 \cdot RC_{mt} + \beta_2 \cdot X_{mt} + \gamma_t + \delta_m + \varepsilon_{mt},$$

where Y_{mt} is the dependent variable (Average Income, Unemployment Rate, Employment Rate, Participation Rate, Rate of Degree Attainment or Total Population) measured in municipality *m* in census year $t \in \{1986, 1991, \ldots, 2016\}$, RC_{mt} is a dummy variable indicating whether or not a municipality *m* had a road connection to Southern Canada in census year *t*, X_{mt} is a vector of two additional covariates (Aggregate Income of the community, Percentage of Indigenous Population) varying for each municipality *m* and each census year *t*, γ_t is the fixed effect for each year *t*, δ_m is the fixed effect for each municipality *m*, and ε_{mt} is a municipality-year-specific error term. All variables are defined in the next section.

The year fixed effects allow to control for trends in time that are common to all municipalities. The municipality fixed effects control for time-invariant factors within a specific municipality. Because of potentially large jumps in aggregate income occurring in certain towns or small cities that experience rapid development due to a large resource extraction project close by, controlling for this variable prevents these changes to be conflated as an effect of road connection. The Aggregate Income confounding variable is omitted for regressions estimating the effect of road connection on outcome variables Average Income and Total Population to avoid multicollinearity issues. This is because Aggregate Income is equal to a multiplication of Average Income by Total Population. The proportion of indigenous inhabitants is also controlled for, as cursory means comparisons seemed to indicate differences between municipalities that have mostly indigenous inhabitants and those that don't. An estimation with the above model is executed for each dependant variable. All analyses were conducted with Stata using fixed-effects panel data functions (version 13).

Further, robustness tests are conducted by estimating outcome values with alternative models with varying combinations after removing year fixed effects, municipality fixed effects and control variables. Nevertheless, our preferred specification is the full model (as specified in (6) in the Appendix tables). In that preferred specification, a robust standard error method known as the Driscoll-Kraay method is employed to ensure the error terms estimated aren't subject to cross-sectional dependence. Because we use panel data between municipalities that are geographically similar, it is possible that spatial dependence would be included in the standard error terms of a DID regression model that does not estimate robust standard errors. Driscoll and Kraay (1998) designed a method that specifically addresses cross-sectional dependence. Failing to account for this type of dependence is known to cause potential biases in standard error estimates. For this reason, we prefer this method to other robust standard error methods.

5.3 Data and Descriptive Statistics

To examine the effect that road connection has on the socio-economic development of remote municipalities in Northern Canada, we estimate our empirical model on a sample of northern communities for which we are able to evaluate outcomes over time while controlling for the characteristics of municipalities that are very different from one another. The provinces of Quebec and Newfoundland-and-Labrador were chosen because of their high level of isolated road construction during the period of time for which data is available.

5.3.1 The sample

To determine whether remote municipalities saw a change in their economic development after the construction of a road connecting them to Canada's primary ecumene, it was important to select a critical mass of towns or villages for which a road was constructed during the period of time studied as well as towns or villages that still had no road constructed by the end of the period of time studied. Each municipality had to:

- be located in Quebec or Newfoundland-and-Labrador;
- be considered part of Northern Canada;
- had to have not been connected by road to Southern Canada before 1986; and
- have a sufficient number of inhabitants for the census to have collected reliable data for each variable.

For this study, the limit between Northern Canada and Southern Canada is established using Hamelin's definition of the North. Hamelin created an indicator known as "VAPO" or "polar value" that can measure the nordicity of a town or locality by generating a score of 1000, where 0 is "least Nordic" and 1000 is "most Nordic". The sum of ten criteria each evaluated on scales of 1 to 100 is calculated to obtain a score on 1000. Six of the ten criteria are strictly geospatial or biophysical (Latitude, Number of summer days, Annual freezing days, Level of permafrost, Levels of precipitation, Vegetation) and four are socioeconomic (Access by road or boat, Access by plane, Population density, Economic activity) (Hamelin, 1968). Similar to a topographic altitude map, Hamelin’s VAPO indicator axis is perpendicular to lines he qualifies as “Isonords”, or lines on a map delimiting the zones of a given VAPO score. From a score of 200 to 300, he considers the zone to be the “Lower Middle North”; from 300 to 500, the “Upper Middle North”; above 500, the “Great North” (Hamelin, 2000). The limit between Northern and Southern Canada used in this study is the 200 VAPO isonord.

It is interesting to note that since “Access by road” is part of the criteria to determine whether a municipality is northern, the very construction of a road could change the VAPO score of the locality, and thus reduce its nordicity. Consequently, for this study, to determine which municipalities were to be analyzed, only the definition of North according to Hamelin before 1986 was taken into account.

The 40 municipalities in Quebec (QC) and Newfoundland-and-Labrador (NL) sampled for the study as well as the year of their road connection, if applicable, are enumerated in Table 5.1. Note that two periods of road construction comprise close to 80% of municipalities connected to Canada’s southern ecumene: 1991-1996 and 2006-2011. The high intensity of road construction in these periods can be explained by the connection of Cree towns in Quebec in the 1990s and two phases of the construction of the Trans-Labrador Highway, completed in 1992 and 2009. For more on the history of road connection in the Quebec-Labrador Peninsula, refer to our previous paper (Stringer and Joanis, in press).

Table 5.1 : List of municipalities in the sample

Municipality	**Year connected by road**	**Province**	**Source (Road Construction)**
Happy Valley - Goose Bay	1992	NL	Higgins and Callanan, 2008
North West River	1992	NL	Higgins and Callanan, 2008
Sheshatsiu	1992	NL	Higgins and Callanan, 2008
Nemaska	1993	QC	Route du Nord, 2020
Eastmain	1994	QC	MTQ, 2020
Wemindji	1996	QC	Wemindji, 2020
Nastashquan (Town)	1996	QC	SRC, 2019
Natashquan 1 (Reserve)	1996	QC	SRC, 2019
Waskaganish	2001	QC	Waskaganish, 2020
Blanc-Sablon	2009	QC	Gov NL, 2012
Bonne-Espérance	2009	QC	Gov NL, 2012
L'Anse-Au-Loup	2009	NL	Gov NL, 2012
Cartwright	2009	NL	Gov NL, 2012
Charlottetown	2009	NL	Gov NL, 2012
Forteau	2009	NL	Gov NL, 2012
Mary's Harbour	2009	NL	Gov NL, 2012
Port-Hope Simpson	2009	NL	Gov NL, 2012
Côte-Nord-du-Golfe-du-Saint-Laurent	2013	QC	SRC, 2019
Akulivik	Not connected	QC	n/a
Davis Inlet / Natuashish	Not connected	NL	n/a
Gros-Mécatina	Not connected	QC	n/a
Hopedale	Not connected	NL	n/a
Inukjuak	Not connected	QC	n/a
Ivujivik	Not connected	QC	n/a
Kangiqsualujjuaq	Not connected	QC	n/a
Kangiqsujuaq	Not connected	QC	n/a
Kangirsuk	Not connected	QC	n/a
Kuujjuaq	Not connected	QC	n/a
Kuujjuarapik	Not connected	QC	n/a
La Romaine	Not connected	QC	n/a
Makkovik	Not connected	NL	n/a
Nain	Not connected	NL	n/a
Puvirnituq	Not connected	QC	n/a
Quaqtaq	Not connected	QC	n/a
Rigolet	Not connected	NL	n/a
Saint-Augustin	Not connected	QC	n/a
Salluit	Not connected	QC	n/a
Tasiujaq	Not connected	QC	n/a
Umiujaq	Not connected	QC	n/a
Whapmogoostui	Not connected	QC	n/a

5.3.2 Outcome variables

Data at the municipal level was collected from the publicly available census profiles of Canada's Census of Population from 1986 to 2016. This time period was chosen because of the easy access to reliable data as well as the constancy of the definitions of data variables during this period. All of the data was retrieved online on the Government of Canada's website, except for the data from the 1986 census, which was retrieved through the Census Analyzer online platform of the University of Toronto's Arts and Sciences Library. As censuses are conducted in Canada every 5 years, data from 7 censuses (1986, 1991, 1996, 2001, 2006, 2011, 2016) were used for this study. Except in 2011, all of the data was collected from the long-form and short-form surveys of each census. In 2011, the Canadian National Household Survey data was conducted in place of the usual long-form census. Statistics pertaining to population, labour, income and education were used.

The variables for which data were collected are explained in Table 5.2.

Table 5.2 : List of variables for which census data was collected

Total Population	Refers to the number of individuals in a particular municipality.
Indigenous Population	Refers to the number of people who identify as having First Nations, Métis or Inuit origins in a particular municipality.
Population 15 years and over	Refers to the number of individuals in a particular municipality whose age is 15 years or over.
Labour Force	Refers to persons who are either employed or unemployed.
Employed	Refers to the number of individuals in a municipality who have a labour force status of "employed". That is, those who: (a) Do any work at all at a job or business, that is, paid work in the context of an employer-employee relationship, or self-employment. This also includes persons who do unpaid family work, which is defined as unpaid work contributing directly to the operation of a farm, business or professional practice owned and operated by a related member of the same household; or (b) Have a job but were not at work due to factors such as their own illness or disability, personal or family responsibilities, vacation or a labour dispute. This category excludes persons not at work because they were on layoff or between casual jobs, and those who do not then have a job (even if they have a job to start at a future date).
Unemployed	Refers to the number of individuals in a municipality who are without paid work or without self-employment work and are available for work and either: (a) have actively looked for paid work in the past four weeks; or (b) are on temporary lay-off and expected to return to their job; or (c) have definite arrangements to start a new job in four weeks or less.
Employment rate	The employment rate for a particular municipality is the number of employed individuals in that municipality, expressed as a percentage of the population aged 15 or over.
Participation rate	The participation rate for a particular municipality is the total labour force in that municipality, expressed as a percentage of the population aged 15 or over.
Unemployment rate	The unemployment rate for a particular municipality is the unemployed in that municipality, expressed as a percentage of the labour force in that municipality.
Average income	Refers to the average total income of an individual in a particular municipality in 2016 constant Canadian dollars. Total income refers to receipts from certain sources, before income taxes and deductions, during the year prior to the census year.
Aggregate income	Refers to the sum of all incomes of all individuals in a particular municipality in 2016 constant Canadian dollars.
No degree, certificate or diploma	Refers to the number of individuals in a municipality that have not earned a degree, certificate or diploma.

With respect to education data, the scarcity of sample data used to infer the number of individuals with specific types of degrees earned in the least populated municipalities meant a significant number of data points were rounded up or down in the censuses, which often led to significant inaccuracy in compiling higher education statistics for this study. Consequently, a different measure of educational progress had to be designed. A new variable, the “Rate of degree attainment” was created. This variable refers to the percentage of the population of a municipality that has earned a degree, certificate or diploma of any kind. Because it is possible to infer that anybody who doesn’t fall into the category of “No degree, certificate or diploma” possesses a degree, certificate or diploma, the new variable is obtained by subtracting the number of individuals from “No degree, certificate or diploma” from that of “Population 15 years and over”, then divided by that of “Population 15 years and over” to obtain a ratio. A “Percentage of Indigenous Population” was also created. It refers to the “Indigenous Population” variable divided by the “Total Population” variable.

5.3.3 Descriptive statistics

Table 5.3 shows comparisons between the means of the variables used in the model, categorized by year, as well as cumulatively for the whole time period studied. Clear time trends are present for several variables in the table. Average Income, Employment Rate, Participation Rate, Rate of Degree Attainment and Aggregate Income increase steadily between 1986 and 2016, indicating that this is a period of economic prosperity for these northern communities. This justifies year-fixed effects controls in further estimations. These controls are necessary to better distinguish what outcomes in municipalities with a road connection are caused by the actual construction of the road rather than a trend relative to all municipalities in time. Furthermore, the municipalities in the sample are far from being monolithic and homogeneous in their characteristics. Important differences in minimums and maximums for all variables indicate that the municipalities examined are vastly different. The large variance in these differences could suggest that the municipalities that have benefited from a road connection differ at some time-invariant level from those that don’t. Some of these time-invariant components will be inevitably impossible to control for, underlining the usefulness of a DID model that can control for municipality-fixed effects.

Table 5.3 : Descriptive statistics of select municipality census data variables; by year

	1986	1991	1996	2001	2006	2011	2016	All Periods
Average Income ($)								
Mean	22292	23364	26134	26914	30005	33596	38804	29027
Std. Dev.	5157	5814	4927	4361	6106	7203	7498	8018
Min.	15648	14581	15730	19223	14217	14286	19568	14217
Max.	35381	35935	42749	42726	50814	50789	58417	58417
Unemployment Rate								
Mean	26.3%	27.3%	28.6%	25.8%	28.0%	21.4%	23.6%	25.9%
Std. Dev.	19.5%	19.8%	17.2%	15.6%	15.1%	12.5%	12.4%	16.1%
Min.	0.0%	3.4%	6.7%	4.2%	7.6%	3.1%	8.2%	0.0%
Max.	76.9%	76.8%	63.4%	66.7%	63.9%	53.8%	53.8%	76.9%
Employment Rate								
Mean	35.1%	40.7%	43.9%	45.4%	46.1%	50.0%	48.6%	44.5%
Std. Dev.	11.0%	13.5%	16.3%	12.3%	13.0%	12.5%	12.6%	13.8%
Min.	13.6%	18.0%	12.5%	22.2%	20.6%	21.6%	24.5%	12.5%
Max.	58.6%	66.8%	70.8%	73.4%	72.1%	73.4%	75.8%	75.8%
Participation Rate								
Mean	50.2%	57.3%	60.1%	61.2%	63.3%	63.4%	63.2%	60.1%
Std. Dev.	14.7%	13.5%	12.4%	8.9%	8.4%	9.7%	9.5%	11.8%
Min.	15.3%	29.4%	20.8%	38.9%	41.3%	32.6%	36.4%	15.3%
Max.	75.5%	79.8%	77.8%	79.5%	80.9%	80.2%	82.6%	82.6%
Rate of Degree Attainment								
Mean	22.3%	29.1%	36.2%	40.3%	45.0%	44.8%	49.3%	38.6%
Std. Dev.	11.5%	12.1%	13.0%	12.8%	11.6%	13.9%	15.6%	15.5%
Min.	4.5%	6.1%	12.8%	20.0%	16.0%	20.1%	18.5%	4.5%
Max.	55.4%	60.2%	77.1%	73.6%	72.3%	77.7%	82.1%	82.1%
Total Population								
Mean	745.5	875.1	912.1	937.5	944.0	1045.9	1025.5	930.2
Std. Dev.	1236.0	1381.0	1338.9	1235.9	1174.8	1284.6	1285.9	1265.5
Min.	135.0	265.0	255.0	300.0	264.0	303.0	290.0	135.0
Max.	7248.0	8610.0	8655.0	7970.0	7572.0	7552.0	8109.0	8655.0
Aggregate Income (millions of $)								
Mean	11.5	14.3	16.7	17.5	20.7	26.1	31.2	20.1
Std. Dev.	25.8	33	32.6	29.8	36.2	47.0	57.8	39.3
Min.	2.3	3.1	3.4	3.9	5.5	6.7	7.5	2.3
Max.	139.0	201.0	206.0	189.0	230.0	275.0	366.0	366.0
Indigenous Population (%)								
Mean	64.0%	57.4%	68.7%	72.2%	73.7%	88.0%	77.5%	71.7%
Std. Dev.	39.4%	40.2%	37.1%	34.5%	33.2%	14.4%	29.9%	34.4%
Min.	0.0%	0.0%	0.0%	1.3%	6.7%	38.5%	9.3%	0.0%
Max.	99.5%	100.0%	100.0%	97.4%	98.9%	100.0%	99.5%	100.0%

Comparing means of treatment and control groups of certain variables over time can highlight whether there is a positive or negative effect associated with road connection. Time-series data can best be illustrated with explicative graphs. Because road connection has occurred in different periods for different municipalities, charting all treatment means versus control means for all municipalities won't be accurate in illustrating a change in trends occurring during the period where roads were constructed. To more properly reflect the reality of road connection, different treatment groups were formed based on the period in which they were connected for means comparisons.

Figures 5.1-5.6 (in the Appendix) illustrate the comparisons of the means of average income, unemployment rate and rate of degree attainment between the municipalities connected during the specified period and the control group. All municipalities that had no road connection between 1986 and 2016 constituted a control group for these graphs. Each graph was divided in three time periods: *Before Construction (B), During Construction (C), After Construction (A). During Construction (C)* refers to the 5-year period in which a road connection was constructed.

Figures 5.1, 5.3 and 5.5 clearly show a change in trend in average income, unemployment rate and rate of degree attainment after the 1991-1996 period, with the treatment group's curve's slope changing steadily over the following 20 years. Figures 5.2 and 5.6 show a similar phenomenon after the 2006-2011 period, with an important increase in average income and a modest increase in the rate of degree attainment for the treatment group. Figure 5.4 doesn't display the same trend for the unemployment rate seen in Figure 5.3, due to an accelerating downwards trend in the treatment group starting as early as 1991. Apart from Figure 5.4, all figures show treatment and control groups following relatively similar trends prior to the treatment period, which helps confirm the parallel trends assumption of difference-in-differences analyses. Moreover, by showing a trend that likely doesn't have anything to do with road construction, the treatment group's curve in Figure 5.4 underlines the need for better control of time-invariant factors pertaining to the municipalities included in that group.

5.4 Empirical Results and Discussion

5.4.1 Main results

Table 5.4 summarizes the regression estimates on the outcome variables using the difference-in-differences method, including controls for year-fixed effects, municipality-fixed effects, confounding variables, as well as Driscoll-Kraay robust standard errors. Comparing cross-data means to these results, the model estimates that having a road connection during a given period is correlated with a decrease in unemployment rate of 6 percentage points, an increase in employment rate of 13 percentage points and an increase in rate of degree attainment of 4 percentage points. All three of these results are statistically significant. These effects are independent of trends over time and of time-invariant characteristics specific to the municipalities. The significance of the estimation for the employment rate ascertains a large standard deviation, which could suggest that while the direction of the effect of road connection on income can be inferred, caution is to be taken as to its precision. This may be a result of the relatively small sample size and high variability of the characteristics of the different municipalities. Effects on the average income, participation rate and total population within a municipality are non-significant when using the Driscoll-Kraay robust standard error method, and thus can be assumed as null for these estimates.

After the construction of a road connection, municipalities that were connected by road saw an increase in their employment rate and rate of degree attainment as well as a decrease in their unemployment rate in subsequent periods. Because of the year-fixed effects and municipality-fixed effects taken into account by the DID method, it can be inferred that these changes in metrics wouldn’t have occurred had a road connection not been built. The year-fixed effects control for the trends that occur in all municipalities over time, while the municipality-fixed effects control for time-invariant characteristics specific to each municipality that could have an impact on the variation of the independent variables. Moreover, confounding variables that change over time were controlled to better hone in on the changes that can be explained by road connection.

Table 5.4 : Summary of the estimated effect of road connection on the outcomes of a municipality

Outcome variable	DID estimate (Std. Dev.)
Average Income ($)	1429.16 (1609.25)
Unemployment Rate	-0.0599** (0.0221)
Employment Rate	0.0132* (0.00626)
Participation Rate	-0.0273 (0.0266)
Rate of Degree Attainment	0.038** (0.0149)
Total Population	-95.20 (54.70)
Observations	249
Year fixed effects	Yes
Municipality fixed effects	Yes
Covariates	Yes
Robust standard error (Driscoll-Kraay)	Yes

*: p < 10%; **: p < 5%; ***: p < 1%

Note: See Appendix for detailed results. These results correspond to column (6) in Appendix tables.

5.4.2 Testing for robustness

Appendices 5.A1-5.A6 (at the end of the document) show the full regression results for the estimates in Table 5.4 as well as different regression results for each outcome variable while removing controls for year fixed effects, municipality fixed-effects, confounding variables or a combination of any of these controls. In all, six different estimates were done for each dependent variable:

(1) shows the results of an ordinary least-squared regression.
(2) shows the results of an ordinary least-squared regression with year fixed effects controls.
(3) shows the results of an ordinary least-squared regression with municipality fixed effects controls.
(4) shows the results of a difference-in-differences model.

(5) shows the results of a difference-in-differences model with controls for confounding variables, i.e., the same results presented in Table 5.4.
(6) shows the results of the same regression as in (5) but with robust standard errors using the Driscoll-Kraay estimation method.

The comparison of results from the different regressions offers important insight concerning the relationships between the variables. Despite removing controls, similar effects can be inferred with most of the outcome variables in which a significant effect is estimated using model (5). Removing controls does not radically change the effect of road connection on Average Income, Unemployment Rate and Rate of Degree Attainment and only alters the values of the estimated coefficients, not their direction or significance. Moreover, the Employment Rate and Participation Rate remain broadly insignificant when removing controls. The Employment Rate only becomes significant when using the Driscoll-Kraay robust standard error method. This could mean that the other regressions in this study fail to take into account cross-sectional dependence that could occur between municipalities that directly affects the Employment Rate. Further, Total Population behaves quite differently when estimated with regression models (1) and (2). This is inevitably a result of taking out municipality fixed effects controls: the large variance in the sample, as can be seen in the descriptive statistics in Table 5.3, makes regressions omitting controls for municipality fixed effects inaccurate.

For the estimates of Average Income and Rate of Degree Attainment, the regression models in (2), (4) and (5) have much more modest results than models (1) and (3), having lower coefficients for these outcome variables. Models (2), (4) and (5) all have controls for year fixed effects, which suggests that improvements in salaries and education follow strong time trends than labour or population variables. This could mean that country-wide trends influencing education and salaries are more ubiquitous and wider-reaching than time trends that influence labour market or population variables. Thus, controlling for these trends was important.

The significance of dependent variables when estimating robust standard errors in (6) paints a different picture than the conclusions drawn from (5). Only the Unemployment Rate and Rate of Degree Attainment figures stay consistently significant the Driscoll-Kraay method for robust standard errors, with the Employment Rate only becoming significant when using that robust standard error method. It can thus be inferred that these three variables are clearly influenced significantly by road connexion. Results pertaining to Average Income and Total Population in regards to estimates from (5) suggest that there is some form of interaction between these variables and road connexion, but that the sample used for this study does not allow to conclusively determine the magnitude or significance of these interactions. Larger sample sizes and more time periods could serve as a way to better explore these interactions.

5.4.3 Discussion

5.4.3.1 Improved labour market conditions

Heightened economic activity could be part of the explanation for lower unemployment experienced in connected municipalities. However, another part of the explanation may lie in the accessibility to jobs rather than job creation, supported by the overall decrease in municipality population count. As Gobillon et al. (2007) have shown, a substantial body of literature has focused on the impact of urban and suburban road development on physically connecting unskilled workers with jobs by reducing spatial mismatch in cities in the United States. Berg et al. (2015) go further by suggesting these conclusions can be applied to a variety of contexts. This is because the mechanism of spatial mismatch applies to many different spatial configurations, not just American urban development. This mechanism "revolves around the role of high transport costs in deterring the unemployed from accepting distant jobs, the harmful effects of long commutes on productivity or decreasing productivity, or high search costs that make the matching between unemployed workers and jobs less efficient." While the argument of lowering long commutes cannot really be applied to the Northern Canadian context, high transport costs deterring unemployed persons accepting distant jobs could be relevant to arctic and subarctic municipalities. Better spatial matching through easier access to remote municipalities may allow local organizations to save on search costs and access a larger pool of applicants that would otherwise be deterred by prohibitive transportation costs to a distant locality.

Amongst the labour market indicators, the unemployment rate and the employment rate are significantly affected by road connection. Since the employment rate uses the number of people employed and the unemployment rate uses the number of people that are unemployed as the numerators in their equations, these indicators usually follow axiomatically an inverse trend. A decrease in unemployment should equal an increase in employment. By applying the spatial mismatch logic explained above, it’s possible to infer that people in small towns who don’t have a job could be using the newly built roads to seek employment elsewhere. Similarly, people from other towns could seek jobs in connected municipalities, increasing the employment rate. Thus, road connection doesn’t unquestionably create jobs in connected municipalities. Instead, it would allow for a better reallocation of human resources within a broader region and more effective job skills matching. The higher value in employment rate change in comparison to unemployment rate change suggests that there could also be net job creation in newly connected municipalities.

5.4.3.2 Better access to education

Transportation and better access to education have been the subject of various studies. Vasconcillos (1997) underlines the importance of physical road access to allow pupils to get to school. Stifel et al. (2016) explain that access to schools is often an overlooked benefit of road construction not factored into studies examining economic development. Jacoby and Minten (2009) and Khandker et al. (2009) quantitatively evaluate the impact of roads on educational attendance and attainment in villages in the developing world, finding positive correlations. All of these studies underline in different ways a fairly similar explanation for this correlation: better physical access and reduced transportation costs make accessing education for inhabitants of areas connected easier.

This is undoubtedly also the case for towns and small cities in Northern Canada. Many smaller towns in the north do not have an establishment that offers professional trades diplomas, let alone university degrees. Accessing one of these establishments when the only available modes of transportation are planes and ships is difficult and bears considerable transportation costs. Many localities are only accessible through air travel that is often prohibitively expensive. Sea travel is limited to the summer, is time-consuming and also relatively expensive. Road access allows citizens to sustainably and more easily connect year-round with neighbouring towns that may have better educational facilities. It also allows northern localities to better connect with Southern Canada, where almost all universities and higher education institutions are located. Figure 5.5 shows how educational attainment in the 1991-1996 treatment group is not only higher than in the control group until 2016 but also rises faster. This shows how road connection conduces perennate educational opportunities for the connected municipalities.

5.4.3.3 Higher average income?

Better wages and poverty reduction have been associated with road construction and road access. Fan and Chan-Kang (2005, 2008), Khandker et al. (2009), Emran and Hou (2013), Donaldson (2018) and Fingleton and Szumilo (2019) link infrastructure construction in rural areas with higher wages and bettered quality of life. The reductions in poverty are a consequence of the diversification of the local economy (Fan and Chan-Kang, 2005; Khandker et al., 2009), new job opportunities that arise from access to other parts of a region (Olsson, 2009), higher wages as a result of production output (Donaldson, 2018) and better access to domestic and international markets (Emran and Hou, 2013). Investment in road construction also provides a greater benefit to the poor than to the not-poor (Khandker et al., 2009), a result of lower living costs.

This study examines the average income of remote communities in Northern Canada. While results of the main regression model with Driscoll-Kraay standard errors note average income changes as insignificant, results from other regressions do infer some degree of significance. This could indicate that road connection to Southern Canada could possibly increase the average income in connected communities, which could be better determined with a larger sample size and more time periods. Even though this study doesn’t successfully demonstrate this interaction, it certainly lays tracks for more research in the area. Such an interaction does have a basis in existing literature, and should be explored more thoroughly given the mixed results in this study.

In the Canadian context, an increase in average income due to road connection could be generally interpreted as an indicator of increased gains from trade between two regions and reduced transport costs (Berg et al., 2015) and increased production (Harchaoui and Tarkhani, 2003). More specifically, this activity could be a result of better access to Canada’s national market, meaning more interregional connectivity with other organizations, institutions and industry branches (Holl, 2004). In turn, this results in a more efficient allocation of funds resulting in higher production, paired with decreased trade costs (Fellows and Tombe, 2018). Ultimately, by increasing local communities’ buying power, together with the possible consumer benefits of cheaper goods by way of lower cost structures, their cost of living is reduced and their quality of life bettered.

5.5 Conclusion

This quantitative analysis has attempted to estimate the effect of road connection of remote municipalities to more populated centers on the economic development of these municipalities. The findings in this paper suggest that there is a correlation between road connection and education and labour market indicators. The difference-in-differences method used in this study is consistent with a large body of literature linking road construction to economic development. Even after controlling for year-fixed effects and group-fixed effects, the estimation model shows that municipalities experience significant gains in educational attainment and employment rate as well as a significant decrease in unemployment rate. Benefiting from a road connection during a given period is correlated with a decrease in unemployment rate of 6 percentage points, an increase in employment rate of 13 percentage points and an increase in rate of degree attainment of 4 percentage points.

Changes in educational attainment and employment can be explained by the increased accessibility associated with the construction of a physical connection between remote localities and urban centers offering more diverse services and opportunities. Proposals for developing Northern Canada and the Arctic have been touted as a new source of productivity and wealth. Local communities in remote parts of Canada have a long history of poverty. For these proposals to be equitable, governments have to take these communities into account and offer solutions that enhance their quality of life. Road connection to the South, while not being a failsafe solution, seems to offer appreciable benefits in this direction.

All in all, this study shows that there is a clear relationship between road connection of isolated areas and economic development in those areas. Extractivism, or development focused solely on natural resources, rarely ensures prosperity for inhabitants of the regions exploited (Acosta, 2013). If governments are going to develop remote resource-rich territories, they should try to generate tangible benefits for the impacted municipalities. This study shows that, minimally, road connection can improve the quality of life by enhancing access to education and job opportunities of local communities in remote locations. Public and private interests should consider these relationships when planning infrastructure and development projects in subarctic and arctic regions.

The limitations of this study include the oversight of estimating other independent variables that could potentially serve as supplementary indicators of certain phenomena discussed above, the lack of international points of comparison and the number of observations. Future research could encompass analyses with such variables to better understand the effect of road connection on the development of remote municipalities. Notably, mobility data could be collected to further understand how many people come to or leave municipalities with road connection, possibly confirming the hypothesis that better labour spatial matching causes the drop observed in unemployment rates. It could also be used to understand the flux of residents leaving the municipalities to obtain better educational credentials. Data on poverty rates could be collected to help get a clearer picture of the true impact on poverty reduction that the results of this study can bring about. Similar methods using municipalities in other countries with identical variables would also shed light on if the effects studied in this article are unique to Canada or are omnipresent throughout the world. Finally, because of the modest sample sizes used, the conclusions of this article have to be apprehended with prudence. Bigger sample sizes and more time periods would augment the predictive power of the mathematical model and guard against differences in results when using robust standard error estimation methods.

CHAPITRE 6 ARTICLE 3: ASSESSING ENERGY TRANSITION COSTS: SUB-NATIONAL CHALLENGES IN CANADA

T. Stringer et M. Joanis ont écrit cet article. Celui-ci a été accepté en 2022 par la revue *Energy Policy*.

6.1 Introduction

Canada's energy transition towards carbon-neutrality has been the subject of much research and speculation. More specifically, the investments required and the changes to the economy that would follow have been purported to be sizable. Whether it be hefty private sector investments (Bataille et al., 2015), government's commitment to significant resources (ECCC, 2016), a progressive phase-out of the fossil fuels sector (Trottier Energy Futures Project, 2016) or the implementation of a comprehensive carbon pricing model (Vaillancourt et al., 2017), the implications of a full renewable energy transition in Canada will undoubtedly have to be thought as an economic dilemma as much as an environmental one. The total cost of such a transition is central to any decision-making on the topic as well as to any of the aforementioned economic considerations. Dolter and Rivers (2018) conclude that the decarbonization of the Canadian electricity sector range anywhere between CAD 8.2 billion and CAD 16 billion annually until 2025 depending on whether inter-provincial transmission lines are built. We find (Stringer et al., 2021) that the costs of a complete pan-Canadian energy transition in all sectors would reach up to CAD 43.3 billion annually until reaching net-zero, followed by fuel savings reaching up to CAD 78 billion thereafter. These are promising findings, as they represent shares of the country's GDP that are not astronomical. They are also well in line with energy transition costs estimated in other parts of the world.

Energy policy in Canada can't be seen as being part of a monolithic plan across the country. Each province has a unique regulatory framework governing electricity production, transmission and distribution and the national electricity market is not fully integrated (Pineau, 2012). Attaining any form of net-zero energy transition in Canada is not possible with a uniform approach. Each province must adopt policies to address its specific challenges in the context of reaching carbon-neutrality (Dusyk et al., 2021). Provinces can broadly be categorized based on whether they possess a large amount of hydroelectricity production capacity. Quebec, Manitoba, British Columbia and

Newfoundland-and-Labrador all produce the quasi totality of their electricity using hydropower. They also share similar regulatory framework structures, with each provincial government owning a large vertically-integrated public utility that owns most of the province's electricity-related infrastructures. They also tend to be highly profitable utilities, often with business plans including energy exports to neighboring provinces or US states. The country's other provinces who do not possess a large capacity of hydroelectric production generally use fossil fuels to produce electricity. Each has a particular regulatory framework, with different degrees of free-market measures in place. Notably, Alberta and Ontario, Canada's fourth and second largest provincial electricity markets respectively, have a power pool in place (Pineau, 2013). This means that it isn't always provincial governments that are responsible for energy infrastructure investments.

67% of all electricity generated in Canada was from renewable sources and 82% was emission-free in 2019. In Quebec, Manitoba, British Columbia, Prince-Edward-Island and Newfoundland-and-Labrador, upwards of 90% of all electricity was produced renewably. However, in Alberta, Saskatchewan and Nova Scotia, fossil fuels account for over 75% of electricity production. Other provinces fall somewhere in between (Natural Resources Canada, 2021). Certain provinces have an electricity sector that employs a majority of renewables while others not. The heterogeneity of the means of electricity production between provinces makes any country-wide cost assessment largely irrelevant to those who have more or less completed the decarbonization of their electricity system. Provinces that don't have renewable production capacity have a few paths to a complete emission-free nuclear-free energy transition, relying mainly on wind or solar energy to replace fossil fuels. These means of production are costly and are in direct competition with cheap local fossil fuel extraction, such is the case in Saskatchewan and Alberta. Much literature has suggested that integrating Canada's electricity market across all provinces would be beneficial economically and environmentally (Pineau et al., 2004; de Villemeur and Pineau, 2012; Pineau, 2012; Pineau, 2013; Siddiqui et al., 2020). Promoting and undergoing an energy transition is thus much easier for hydroelectricity-producing provinces. The gap between provinces with different energy mixes and the potential benefits of inter-provincial integration highlight the need in evaluating Canada's energy transition costs on a provincial basis. Such an analysis has yet to be done.

As mentioned above, existing research suggests that a pan-Canadian transition is relatively affordable. What are the expenditures associated with a net-zero energy transition in each of Canada's provinces? What fossil fuel savings can be expected following a net-zero transition?

Which provinces stand to gain the most from a transition? What policies can governmental stakeholders enact to achieve a transition?

This paper uses the results of the NATEM simulation model used by the Trottier Institute in their 2021 Canadian Energy Outlook (Langlois-Bertrand et al., 2021). The research in this paper is directly linked to our prior research concerning energy transition costs in Canada (Stringer et al., 2021). Province-specific energy consumption and electricity production figures for each of the five scenarios in the NATEM model were collected for years 2030, 2040, 2050 and 2060. We use a cost-based approach based on Heal's model (2020) to calculate the infrastructure expenditures and the fossil fuel savings associated with these five scenarios over time. We find that all provinces will benefit from an energy transition. Our past research (Stringer et al., 2021) showed that Canada as a whole would benefit from cost savings following an energy transition. This article shows that each province would also benefit from similar savings individually. We find that the provinces that produce electricity using fossil fuels, such as Saskatchewan and Alberta, are those who will benefit the most economically from a pan-Canadian energy transition, while those who already produce electricity using renewable sources, such as Newfoundland-and-Labrador, British Columbia and Quebec, have less of an incentive to undergo a transition, as their electricity sector is already sustainable.

The rest of the paper is structured as follows. Section 2 surveys the existing literature pertaining to the economic aspects of an energy transition. Section 3 outlines the empirical model. Section 4 presents the study's main findings. Section 5 discusses the policy implications of these results and concludes.

6.2 Literature review of the economic aspects of an energy transition

The transition to renewable energy is a concept that is still in its infancy. No country in the world has yet undergone a complete transition from non-renewable energy sources to non-hydro renewable sources for producing electricity. Governments worldwide face resistance when proposing plans to undertake such a transition because of the supposed high cost of transitioning. However, an evolving body of literature posits that an energy transition isn't necessarily as costly or destabilizing as one might think and may invoke important long-term economic benefits.

Several researchers have sought to understand what kind of impact an energy transition would have on the global economy. D'Alessandro et al. (2010) emphasize that a gradual transition to renewable sources would be sustainable and wouldn't automatically lead to null or negative GDP (Gross Domestic Product) growth. Garcia-Casals et al. (2019) suggest that a worldwide energy transition from 2018 to 2050 would lead to increases in global GDP, country-specific GDP and employment. Nieto et al. (2020) not only affirm that GDP increases could result from an energy transition, but also that transitioning to renewable energy may be the only way to ensure some GDP growth in the future, albeit being slower than in the last few decades[1]. Bogdanov et al. (2021) assert that low-cost electricity is a feasible way to answer world energy demand while limiting the impact of climate change. They assess that infrastructure costs to produce and distribute renewable energy will constitute the biggest part of energy expenditures in the future, as fuel consumption would become quasi-inexistent and thus not represent a significant cost. These large infrastructure cost predictions are in line with Režný and Bureš' (2019) findings, who calculated that a global energy transition would require an investment-to-GDP ratio close to that encountered in wartime spending[2].

When looking at the country-specific or region-specific contexts of the economic impact of decarbonization, the analyses seem to present rather mixed conclusions. At the macro-regional level, Victoria et al. (2020) reaffirm the magnitude of these expenditures for Europe but highlight the important cost reductions that could be captured by investing in decarbonization early on in the transition process. Capros et al. (2014) found that for the EU (European Union), an 80% emissions reduction target would only require costs at the height of 1% of GDP or less from 2015 to 2050.

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[1] There is an implicit assumption in most of the literature that economic development requires more energy. Yet, there is an alternative view of development that emphasizes degrowth. Such a scenario would also present an interesting opportunity for decarbonization by reducing the need for increases in electricity production (Kunze and Becker, 2015; Gunderson et al., 2018). Collective ownership of the energy system can empower local communities and make them central stakeholders in their own decarbonization. Instead of replacing fossil fuel generation capacity, less electricity could be consumed and nothing could be built to replace it. Cost-wise, this is an interesting proposition. However, local initiatives have proven at times to not necessarily reduce energy use (Tsagkari et al, 2021).

[2] As an element of gross fixed capital formation, infrastructure investments add to the GDP. Only the import of materials or products to implant the infrastructures would lower GDP.

D’Aprile et al. (2020) indicate that a similar figure of 1% of additional investment is needed to complete an energy transition in the EU. At the country level, several studies have evaluated the economic impact of a transition. Sadiqa et al. (2018) assert that a transition to renewable energy systems would be the least costly option for Pakistan in the near future. Kilickaplan et al. (2017) find that an energy transition, while costly in the beginning, would allow Turkey to free itself from fuel imports and significantly lower electricity production costs by 2050. Fortes et al. (2019) conclude that capital costs for a transition in Portugal between 2015 and 2050 wouldn’t be costlier than expenditures in the oil and gas sector to date. In the United Kingdom, Allan et al. (2020) even assert that the energy transition will play a key role in the coronavirus economic recovery.

Germany is of particular interest when discussing future energy transitions since the country is already conducting one of the largest real-life energy transition experiments in the world. Because the institutional and infrastructural frameworks needed for an energy transition are already in place, predictions on the economic impact of their energy transition are less speculative than in countries where such a transition hasn’t yet been undertaken. Lehr et al. (2012) found that an energy transition will create jobs in Germany by 2030. Blazejczak et al. (2014) predicted that by the same date, Germany will also experience higher economic growth due to renewable energy expansion. Andor et al. (2017) expose the ineffectiveness of Germany’s feed-in tariff system for renewables and the exponential increase in electricity costs, the highest amongst OECD countries, that German residents and businesses have experienced since 2010. This increase in the cost of living is despite the 0.8% of GDP invested in renewable energy efforts and modest changes in carbon emissions. Unnerstall (2017) recognizes the downsides of the German energy transition but offers a fair explanation for these shortcomings. He says that Germany’s energy transition was initially billed as a nuclear phase-out project. While nuclear energy isn’t a renewable source of power, it isn’t a fossil fuel either and doesn’t produce carbon emissions. Thus, the renewables installed during the first decade of the transition were commissioned to replace nuclear power plants, not fossil fuel electricity generation capacity. As an early adopter of green technologies, Germany transitioned when the price of renewable energy technology was at its highest. Unnerstall calculates the cost of a transition if it occurred between 2017 and 2030 and finds that the same decarbonization efforts made so far would only cost around 0.15% of the country’s GDP had it been undertaken now instead of before. His article also shows the evolutive nature of energy transition projects: because of rapidly changing renewable energy technology costs, a transition tomorrow is cheaper than a transition yesterday.

Heal (2020) conducts similar modelling for the American context with a few additional parameters. He attempts to understand the cost of transitioning all of the fossil fuel electricity production capacities by solar and wind generation in the United States between 2020 and 2050. To make his analysis more sensible, he added energy storage costs and transmission costs to the total cost, while subtracting fossil fuel costs and stranded assets that would have to be replaced. With an annual total cost of USD 6.1B, Heal states that an energy transition in the US would roughly represent an extra 0.02% of GDP of spending after deducting fuel savings and savings from infrastructures that don't have to be replaced. A consensus can be formed to say that an energy transition is probably not catastrophically costly. All in all, the cardinal rule for establishing the cost of transitioning seems to be to take into account the specificities of the context of a country or region.

Overall, cost assessments have been done at the national or supranational level, with few analyses breaking down results by sub-national political boundaries. Sadiqa et al. (2018) and Kilickaplan et al. (2017) do examine costs based on sub-national regions, but these regions are defined based on technical considerations rather than political boundaries. Dolter and Rivers (2018) do undertake a certain degree of analysis for each Canadian province, but mostly examine the power lines between provinces in regards to electricity transmission. No study has yet evaluated the specific costs that would have to be incurred by each Canadian province.

6.3 Methodology

We apply a cost-based mathematical approach to quantify the expenditures and savings related to an energy transition for each of Canada's provinces. Our analysis is based on the one used by Heal in his 2020 paper. We use electricity generation figures classified by mode of electricity production and by province as well as total energy consumption by province by type of energy. Both of these data sets were obtained as outputs from the NATEM simulation model used by the Trottier Institute. We focus on establishing an annual dollar figure for each of Canada's 10 provinces, each time period and each scenario (Table 6.1), as well as an understanding of which provinces stand most to gain from an energy transition.

Table 6.1: Description of the reference and carbon emission reduction scenarios

Name	Description
REF	The reference scenario. This scenario presents results using no constraining GHG reduction targets. Macroeconomic assumptions (GDP, population, oil and gas export prices) are aligned with the Reference scenario used in Canada Energy Regulator's Energy Future 2020 outlook (CER 2020), imposing no additional constraints in terms of GHG emissions reductions, but including policies already in place.
CP30	This scenario takes REF and adds the carbon pricing increase schedule announced by the federal government in late 2020, with a price reaching \$170/tonne of CO_2e in 2030. To accelerate the impact of carbon pricing, this scenario also lowers the minimum rate of return with respect to standard practice.
NZ60	This scenario imposes a net-zero emissions target on total CO_2e by 2060, a 30% reduction by 2030, and an 80% reduction by 2050 (with respect to 2005). This reflects the prior Canadian targets, extended to reach net-zero in 2060. Macroeconomic assumptions for all NZ scenarios are aligned with the Evolving scenario used in the CER Energy Future 2020 outlook (CER 2020).
NZ50	This scenario imposes a net-zero emissions target on total CO_2-eq by 2050, and a 40% reduction target by 2030, with respect to 2005. This corresponds most closely to the current government's targets.
NZ45	This scenario imposes a net-zero emissions target on total CO_2-eq by 2045 and a 45% reduction target by 2030.

Source: Langlois-Bertrand et al., 2021

The model used for this study is a cost-based approach that calculates the differences in annual infrastructure and fossil fuel expenditures in comparison to 2016 levels. It is inspired by Heal's (2020) decarbonization model used to estimate the cost of transition in the United States. It closely resembles the model used in our previous research (Stringer et al., 2021): the main differences are the adoption of five time periods instead of four and the use of provincial-level data, yielding ten different sets of results, one for each province rather than one for all of Canada.

6.3.1 The cost-based model

The following model was applied to each province's electricity generation and fossil fuel consumption data. The annual cost of an energy transition for each of Canada's provinces is calculated using the following equation[3]:

$$C_{sp} = I_{sp} + F_{sp} \tag{1}$$

where C_{sp} is the total net annual cost of an energy transition by scenario s where $s \in$ (REF, CP30, NZ60, NZ50, NZ45) and time period p where $p \in$ (2016-2030, 2030-2040, 2040-2050, 2050-2060, 2060+), I_{sp} are the annual additional infrastructure expenditures by scenario s and time period p, F_{sp} are the annual additional fuel costs by scenario s and time period p.

$$I_{sp} = D_{sp} + E_{sp} + G_{sp} \tag{2}$$

[3] It is important to note that all infrastructure and fuel cost figures refer to current benchmark costs. We do not account for changes in costs due to changes in market prices. Infrastructure costs are likely to decrease over time as a result of new economies of scale achieved and better sourcing of materials. However, these cost decreases are not definite and many risks exist, such as geopolitical threats to regions from where materials are sourced or bottlenecks in land use that will limit the capacity to install certain types of renewable energy generation sources. Fuel costs are generally unpredictable. For example, over the last 20 years, the price of a barrel of Brent crude oil has fluctuated greatly. Many different factors, including political decisions by OPEC or global events such as the COVID-19 pandemic, have made it difficult to predict with accuracy future trends in fossil fuel prices. Increasing fossil fuel scarcity may make prices rise over the next 40 years. Oppositely, prices may fall if many countries transition to renewable energy sources and choose to use less fossil fuels. To make sure that our analysis is not overly optimistic in predicting how the risks enumerated above will play out, we assume that infrastructure costs and fuel costs do not change over time. In short, our analysis should not serve as a conclusive depiction of what will happen from now until 2060, but rather a general understanding of the relationship between infrastructure costs and fossil fuel savings incurred by decarbonization.

where D_{sp} is the annualized additional generation capacity investment cost by scenario s and time period p, E_{sp} is annualized additional transmission investment cost by scenario s and time period p, G_{sp} is annualized additional storage investment cost by scenario s and time period p.

Equations 3 and 4 calculate the changes in power generation capacity and fuel consumption over time for each scenario:

$$A_{msp} = x_{ms_t} - x_{ms_{t-1}} \tag{3}$$

where A_{msp} is the change in power generation capacity (kW) by power generation mode *m* where $m \in$ (Hydro, Biomass, Wind, Solar, Nuclear, Coal, Natural Gas, Oil), scenario *s* and time period p, x_{mp_t} is the power generation capacity (kW) by power generation mode *m* and scenario *s* for year *t* where *t* ∈ {2016, 2030, 2040, 2050, 2060}, $x_{mp_{t-1}}$ is the power generation capacity (kW) by power generation mode *m* and scenario *s* for the previous year for which data was collected $(t - 1)$.

$$B_{nst} = y_{ns_t} - y_{ns_{t_0}} \tag{4}$$

where B_{nst} is the change in fossil fuel consumption (PJ) by type of fossil fuel *n* where *n* ∈ (Coal, Natural Gas, Oil), scenario *s* and year *t*, y_{ns_t} is the fossil fuel consumption (PJ) by type of fossil fuel *n* and scenario *s* for year *t*, $y_{ns_{t_0}}$ is the fossil fuel consumption (PJ) by type of fossil fuel *n* and scenario *s* for 2016 (t_0).

6.3.2 Infrastructure expenditures

Infrastructure expenditures encompass generation capacity costs, transmission costs and energy storage costs:

- Generation capacity costs refer to the investments required to construct the facilities to produce new power capacity, notably windmills, solar panels, hydroelectric dams, nuclear plants or thermal plants to name a few. It is considered that a negative value for a mode of electricity production means that less generation capacity of that type of electricity is required. For this reason, we consider that such assets wouldn't have to be replaced and represent a cost savings.

- Transmission costs refer to the investments required to construct the power lines that would connect new production capacity to demand centers. This amounts to the number of kilometers of power lines that would have to constructed to service new generation capacity. To find this number, we assumed that power lines were to be constructed proportionately to any additional electricity generation capacity. We used Heal's (2020) base measurements of 50 000 miles of high voltage power lines for 2.44 billion MWh of additional annual power generation capacity with the change in MWh of renewable electricity production capacity in Canada to calculate the length of high voltage power lines that have to be built in each scenario for each period.
- Energy storage costs refer to medium-term battery storage investments that are required to ensure stability to electricity generation modes that do not constantly produce electricity, such as solar panels and windmills. For the needs of our model, and as in Heal's model (2020), we posit that two days of battery storage are required for all new generation capacity using these two technologies.

Equations 5, 6 and 7 express these costs in mathematical terms:

$$D_{sp} = \frac{\sum_{m=1}^{k}\left(A_{msp} \times P_m\right)}{z_p} \tag{5}$$

where P_m is the cost of power generation capacity (CAD/kW) by power generation mode *m* (Table 6.2), z_p is the number of years in a period *p*. It is important to note that the figures used from Table 6.2 were divided by the capacity factors of the modes of generation.

Table 6.2: Cost of power generation capacity divided by capacity factor

Generation mode	P_m ($/kW)
Hydro	14,011
Biomass	4,916
Wind	4,420
Solar	6,274
Nuclear	9,165
Coal	4,637
Natural Gas	1,121
Oil	831

Source: Langlois-Bertrand et al., 2021

$$E_{sp} = \frac{L_{ps} \times Q}{z_p} \tag{6}$$

where L_{ps} is the length (km) of high voltage power lines to be built by scenario s and time period p, Q is the cost of a high voltage power line (CAD/km). For this study, we used Dolter and Rivers' (2018) figure of CAD 2.4M by kilometer.

$$G_{sp} = \frac{(R_{ps} + S_{ps}) \times W}{z_p} \tag{7}$$

where R_{ps} is the additional energy storage capacity required due to additional wind generation capacity (kWh) by scenario s and time period p, S_{ps} is the additional energy storage capacity required due to additional solar generation capacity (kWh) by scenario s and time period p, W is the cost of energy storage capacity. Schmidt et al. (2019) predict that lithium-ion battery costs could be close to 25% in 2050 of what they are in 2020. Given the decreasing price of battery storage with strong downwards trends and a price of 140 USD/kWh in 2020 (BloombergNEF, 2021), we use a conservative figure of 100 CAD/kWh for the all periods in our study.

Costs related to electricity distribution were not included in the model. Changes in the technology required to service new generation and transmission infrastructures will unquestionably play a big role in Canada's energy transition. Smart-grids that can better estimate the amount of energy needed to be produced in real time will incur important investments in the future. Networks that can better regulate contemporary electricity management issues such as prosumers that feed electricity into the main grid, demand response to reduce consumers' electricity costs or vehicle-to-grid systems that would reduce the necessity for grid-level storage could become commonplace. We did not include the costs related to these developments in our model because of their speculative nature. Much of these technologies haven't been deployed at a large scale, and it is difficult to obtain accurate figures based on additional generation capacity, the basis of our model.

6.3.3 Fuel costs

An energy transition that replaces fossil fuels with electricity produced by renewable sources will inevitably decrease the consumption of fossil fuels, notably to produce electricity, but also in transportation and heating applications. Thus, net-zero transition scenarios are likely to present important cost savings related to this decrease in fossil fuel consumption after the transition.

$$F_{sp} = \sum_{n=1}^{i} B_{nst} \times V_n \tag{8}$$

where V_n is the fossil fuel cost (CAD/PJ) by type of fossil fuel *n* (Table 6.3). It is important to note that the year t in B_{nst} corresponds to the lower bound of period p in F_{sp}. This means that it is assumed that there are no additional fuel costs or savings in the first period (2016-2030).

Table 6.3: Cost of a fossil fuel type by unit of energy

Fuel type	FC_X (\$/GJ)
Coal	2.5
Natural Gas	2.5
RPPs	25

The values in Table 6.3 are benchmark prices that are meant to give an order of magnitude to the cost of energy extracted from fossil fuel use. As mentioned previously, fossil fuel prices are subject to very important fluctuations in price. We used fairly conservative cost estimates for fossil fuels to strengthen the hypothesis that even with lower price values, fossil fuel savings can be significant. For coal, we use the average price of 36.14 USD/ton (EIA, 2021a) and an energy content of 18 MMBtu/ton. The average for all types of coal in the US is around 20 MMBtu/ton (EIA, 2021b). Unlike in the US, lignite is used for much of Canada's electricity production, notably for all of

Saskatchewan's electricity production, and has an energy content anywhere from 9 to 17 MMBtu/ton (EIA, 2021c). For this reason, we use 18 MMbtu/ton as a more reasonable hypothesis. For natural gas, we use a price benchmark on the lower end of the Henry Hub gas spot price history from 2011 to 2021 of 2 USD/MMBtu (EIA, 2022). For RPPs, we use an aggregate value of 1 CAD/l and an energy content of 0.4 GJ/l, which is an average of the energy content of most conventional RPPs (World Nuclear Association, 2022). The 1 CAD/l standard value is an aggregate of lower-bound prices for different types of RPPs (gasoline, diesel, fuel oil, kerosene) based on the Natural Resources Canada's *Transportation Fuel Prices* charts from 2011 to 2021. A conversion rate from USD to CAD of 1.32 is used, the Bank of Canada average for 2016-2020. An engineering conversion rate of 1.0551 GJ per MMBtu is used. Taxes are not accounted for in the fuel prices in this study.

6.3.4 Discount rate

We use a discount rate to determine the present value of cash flows in the future. The discount rate that we use is one of 3% per year for all cash flows in this study. We choose to use the discount rate used by the National Oceanic and Atmospheric Administration (NOAA, 1999), which is in line with discount rates used by different world governments in the context of public energy infrastructure projects (Steinbach and Staniaszek, 2015). Because time periods in this study group different years together, we calculate the multi-annual compound discount rate from 2016 to each year in the period. We multiply the average of all of these compound rates by the total annualized expenditures and fossil fuel savings in the period.

Applied to the total net annual cost, the discount rate formula for a time period is given by:

$$C_{sp}' = C_{sp} \times \frac{1}{z_p} \sum_{i=1}^{z_p} \frac{1}{(1+d)^{LB_p + i - 2016}} \tag{9}$$

Where C_{sp}' is the total net annual cost of an energy transition by scenario s and time period p with a discount rate applied, LB_p is the lower bound year of period p, d is the social discount rate.

This equation also applies to I_{sp} and F_{sp}.

6.3.5 Comparing the provinces

To ascertain the importance of an energy transition for each province relative to the size of their economies, we calculate the difference between the reference scenario (REF) and the net-zero by 2045 scenario (NZ45) using a timeframe of 44 years (2016-2060) and provincial GDP. These scenarios are chosen because they are the most qualitatively and quantitatively different. Equation 10 defines the difference between both scenarios in terms of investment expenditures: a greater difference between both scenarios means that a transition is more costly. Equation 11 defines the difference between both scenarios in terms of fuel savings: a greater difference between both scenarios means that a transition generates more fuel savings. Equation 12 defines the difference both scenarios in terms of net cost: a greater difference between both scenarios means that a transition is more beneficial for a province since there is more to save fuel wise from transitioning.

$$ICD = \frac{\sum_{p=1}^{j}\left(I_{NZ45p} - I_{REFp}\right) \times z_p}{GDP \times TY} \tag{10}$$

where ICD is the annual transition infrastructure expenditure difference between the two scenarios between 2016 and 2060, where a higher value expresses a higher level of infrastructure expenditures and a lower value a lower level, GDP is the value of provincial GDP per province in 2019 (Table 6.A6), z_p is the number of years in a period p, TY is the total number of years used for this calculation, in this case the difference between 2016 and 2060, 44 years. ICD can be understood as the annual additional percentage of GDP that has to be invested when attaining a net-zero transition by 2045 on an annual basis from 2016 to 2060 in comparison with the reference scenario.

$$FCD = \frac{\sum_{p=1}^{j}\left(F_{NZ45p} - F_{REFp}\right) \times z_p}{GDP \times TY} \tag{11}$$

where FCD is the annual transition fuel savings difference between the two scenarios between 2016 and 2060, where a lower value means higher fuel savings and a higher value means lower fuel savings. FCD can be understood as the annual percentage of GDP that would be saved from attaining a net-zero transition by 2045 on an annual basis from 2016 to 2060 in comparison with the reference scenario.

$$NCD = \frac{\sum_{p=1}^{j}\left(C_{NZ45p} - C_{REFp}\right) \times z_p}{GDP \times TY} \qquad (12)$$

where NCD is the annual transition net cost difference between the two scenarios between 2016 and 2060, where a lower value means higher overall savings and a higher value means lower overall savings. NCD can be understood as the net percentage of GDP that has would be saved after factoring in infrastructure expenditures when attaining a net-zero transition by 2045 on an annual basis from 2016 to 2060 in comparison with the reference scenario. In line with Equation 1, NCD is the sum of ICD and FCD for each province.

Because Canadian provinces are vastly different in terms of population and economy size, using GDP was a way to compare the implications of the costs and savings of a transition across a varied panel of socio-geographic regions. The figures serve as a broad understanding of the magnitude of a transition rather than to accurately track which share of the economy would have to be invested in renewables. Constant GDP values were used, and for this reason, caution should be applied when using the results in this study.

6.4 Results

Table 6.4 ranks the provinces in order of benefits associated with the energy transition. The ranking starts with the province with the most net savings following an energy transition using descending values of NCD. The table also compares NCD, ICD and FCD values. Overall, provinces that are hydro-dominated have less to invest in an energy transition. The three most populous provinces are at the bottom of the ranking, meaning that for provinces with bigger economies, the overall burden proportionate to the size of the economy of transitioning is smaller. This suggests there are economies of scale to be captured, indicating these same economies of scale could be replicated at a national level. It is also to be noted that Saskatchewan and Alberta, two provinces in which the oil and gas sector is particularly important, rank first in net cost difference and fuel savings. Provinces in which fossil fuels are more important, an energy transition is more interesting due to larger fossil fuel savings to capture post-transition.

Table 6.4: Comparing the provinces by transition costs and savings relative to GDP

Province	NCD (%)	ICD(%)	FCD(%)
Saskatchewan	-0.72	1.26	-1.98
Alberta	-0.63	0.64	-1.27
Prince-Edward-Island	-0.59	0.44	-1.03
Nova Scotia	-0.57	0.42	-0.99
Manitoba	-0.53	0.61	-1.14
New Brunswick	-0.20	0.83	-1.03
Quebec	-0.16	0.30	-0.46
Ontario	-0.13	0.53	-0.66
British Columbia	0.08	0.50	-0.42
Newfoundland-and-Labrador	0.09	0.56	-0.48

Table 6.A1 in the Appendix summarizes the results of the model in dollar figures. Table 6.A2 in the Appendix summarizes the results of the model as percentages of provincial Gross Domestic Product (GDP). Because Canada's provinces are vastly different in size, population and economy, using an annual nominal GDP value for each province (Table 6.A6) allows us to compare the relative costs of the energy transition scenarios proposed in this study. Tables 6.A1 and 6.A2 show the results for each province, for each time period, for each scenario. Negative results represent savings while positive results represent expenditures/costs. The results show important differences between the provinces in terms of the benefits relative to implementing a plan that seeks to achieve carbon-neutrality.

Most provinces stand to benefit from an early adoption of a net-zero plan in order to avail from the subsequent fossil fuel savings incurred as quickly as possible. Generally, for any given province, the least infrastructure expenditures and the most fuel savings occur during the NZ45 scenario. Much less financially interesting than the net-zero plans, the federal government's carbon pricing plan, as simulated in scenario CP30, incurs savings by 2060 for 4 provinces. The average annual difference between REF and NZ45 in percentage of GDP allocated as infrastructure expenditures (Table 6.4) for all provinces is at 0.61% for 2016 to 2060. Annual infrastructure expenditures are mostly outweighed by the annual fuel savings they entail, staying largely in the 1-2% of GDP range for periods in which heavy investment is required. Only for Newfoundland-and-Labrador and Saskatchewan do the hard costs of transitioning go over 2% of GDP at some point. These numbers are far from what could be considered "wartime spending" (Režný and Bureš, 2019), but they cannot be indiscriminately assimilated to the 1% of GDP figure promised in other existing literature (Capros et al., 2014; Andor et al., 2017; D'Aprile et al., 2020). The fluctuations in costs over time mean that provinces will have phases with more investment and phases with less investment. Our model is able to pinpoint when these phases of heavy investment will occur, as seen in Tables 7.A1 and 7.A2. This partially confirms the affordability hypothesis of a net-zero energy transition. Also, fuel costs arising from not transitioning or fuel savings captured after transitioning are largely overlooked in this same literature. Future fuel savings largely outweigh infrastructure expenses, so it is feasible to assert that it is financially advantageous to invest in a net-zero transition. This study clearly shows that infrastructure investment in clean energy leads to constant fossil fuel savings in the future. In fact, because of this causality link, any future study on the topic of cost assessments of energy transitions should minimally examine fossil fuel consumption as a corollary to infrastructure expenditures. Furthermore, the results confirm the hypothesis that an energy transition undertaken in Canada will benefit each province individually since all provinces will benefit to some extent in the end.

Different provinces incur different average annual costs (Table 6.4). Even if each province stands to benefit from an energy transition, some provinces stand to benefit more than others, as is perceptible in Table 6.4. Each province takes a different decarbonization pathway based on the existing energy mix being consumed. This influences the differences in cost magnitudes in Tables 6.A1 and 6.A2.

Pineau (2013) notes that while all provinces each have individual characteristics, they can be classified into three main groups: hydropower-dominated, restructured or traditional. Table 6.A5 shows these distinctions clearly. Traditional refers to provinces that mostly have a fossil fuel-dominated electricity mix. His division of Canadian provinces is partially visible in the breakdown in the results of the section above. Traditional provinces, such as Alberta, Saskatchewan and to some extent Nova Scotia, have the greatest incentive to undergo an energy transition. Hydropower-dominated, such as Newfoundland-and-Labrador, British Columbia and Quebec, have less incentive. Manitoba is somewhat of an exception, due to its increasing dependence on fossil fuels for sectors outside of electricity production. All the “restructured” provinces are somewhere in between these two groups.

Sensitivity analysis

To test the effect of different discount rates on the results, we also run the model with annual discount rates of 0% and 6%. Tables 7.A3 and 7.A4 show results with a 0% discount rate. The discount rate has a fairly predictable effect, by reducing the value of future cash flows in time periods that are further from the baseline year, in this case 2016. When comparing Table 6.A4 to Table 6.A2, we see that fossil fuel savings that can be captured from 2040 onwards are far greater when no discount rate is applied. Applying a 3% discount rate makes the investment to fossil fuel savings ratio larger. This is because fossil fuel savings are captured later and are more discounted. Using a 6% discount rate further accentuates this trend, by reducing fossil fuel savings even more, to a point where the fossil fuel savings are not worth the initial investments for roughly half of the provinces. The fact that fossil fuel savings become smaller and smaller with higher discount rates makes the choice of a social discount rate very important when evaluating renewable energy projects. It may also explain why many provinces have not yet seriously invested in renewable generation infrastructure: the initial costs are high and the potential benefits are too far ahead in time to be valuable in the present.

6.5 Conclusion and Policy Implications

The results in Section 4 show different investment needs for each of Canada’s provinces as well as different levels of fuel savings. The provinces that produce electricity using fossil fuels have the strongest incentive to invest in renewables to unlock better fuel savings thereafter. Those that produce electricity largely using renewable sources have less savings to capture. Every provincial government has put in place a different climate change policy plan, with different provisions for the decarbonization of the electricity, residential, industrial, agricultural and transportation sectors. Because every province essentially functions as its own energy market with little to no coordination between each of them, provincial governments are the most important policymakers in decarbonization. As a first step in Canada’s energy transition, investing in renewables and the policy decisions that accompany these investments must be done according to each province's market structure. Each provincial government has to commit to individually invest important sums in renewable energy infrastructures for Canada's transition to be completed. While integration of Canada's electricity market has been suggested as a possible solution for the country's energy transition, such a policy would require high levels of coordination and possible changes to Canada's Constitution. In the short-term, provincial, regional and federal policies that help provinces transition individually can be enacted to promote an energy transition. In the long-term, network integration bolstered by the federal government could also be executed.

6.5.1 Provincial investments in renewable generation capacity

Our results show that each province needs to invest a sizeable proportion of its GDP in renewables to attain a carbon-neutral energy transition. While this isn't a particularly surprising finding, the differences between Canada's provinces in how they produce electricity emphasize the imperative of investing in renewables. Depending on their current energy mix, each province will be faced with either transitioning from fossil fuels to renewables, or ramping up existing renewable electricity production to cater to developing demand. This means that each province needs to invest in renewable electricity production to attain a transition individually if a 2045, 2050 or 2060 target is aimed for.

Producing more green electricity can essentially be accomplished using two different infrastructure investment pathways. The first is to increase hydroelectricity production by constructing dams and reservoirs. The second is to build wind turbines and solar panels. Except for Prince-Edward-Island, the provinces in Canada that already feature a low-carbon electricity system have adopted the first pathway. Usually, these kinds of infrastructures are large projects that incur immense costs that can only be assumed by a government monopoly. Unfortunately, the provinces that currently produce the most of their electricity using fossil fuels and that could capture the greatest potential gains from a transition, such as Alberta, Saskatchewan and Nova Scotia, have already used up most of their hydroelectric potential and need to examine other avenues towards a transition. The simulations done by the Trottier Institute (Langlois-Bertrand et al., 2021) show that these provinces would likely adopt the second pathway to attain carbon-neutrality.

Financing solar and wind energy can be done through public or private entities. Provinces that have a public utility market structure with a monopolistic crown corporation, such as Saskatchewan, would rely on government investments in solar or wind energy infrastructures to ensure a transition. This puts a lot of pressure on provincial governments that already incur annual deficits, who would have to charge higher prices for electricity to finance these new investments. Provinces that rely on a market structure that allows for private firms to compete, such as Alberta, would likely have to implement some sort of feed-in tariff policy or subsidy to incentivize these firms to invest in renewables. A feed-in tariff policy is an agreement between the government and renewable electricity producers for producers to receive a premium over several years, increasing the attractiveness of investing in clean energy. Such a policy could raise the price of electricity and garner public resistance, which is what happened in Germany since the beginning of their energy transition. Generation capacity infrastructure investment has to potential to raise electricity prices and make public support scarce. Instead of increasing electricity costs, progressive taxes specific to energy could help fund these infrastructures and relieve the people that can't afford high electricity costs of the burden of a transition.

Investing in renewables also entails investing in new transmission and storage infrastructures. Because of the intermittence of electricity production when using wind turbines or solar panels, large-scale energy storage, such as chemical batteries, pumped air storage or pumped water storage, are necessary to ensure citizens a constant supply of electricity. Much like hydroelectric dams, most wind turbines and solar panels have to be located in remote areas outside of city centers. This increases the need for additional means of transmission, namely power lines connecting urban centers to power generation in rural areas. Like generation capacity, the costs associated with these infrastructures would be assumed by public utilities or private companies. Depending on the province's electricity market structure, this could make electricity costs higher if these organizations aren't able to capitalize on network improvements resulting from new transmission and distribution infrastructure.

Canada is also, on a per-capita basis, one the world's largest energy consumers (IEA, 2021). The fact that Canada has close to no geopolitical threats and a cheap and plentiful energy supply brings about inefficient energy consumption. Increasing energy efficiency would be an easy way to reduce total energy consumption, decrease fossil fuel usage, capture savings and make renewable energy investments decarbonize a larger share of Canada's energy mix. Provincial governments can invest in projects that promote more efficient energy consumption, such as public transit infrastructure, more energy-efficient buildings using frameworks such as LEED, Energy Star and Passive House or long-distance train travel. These investments would allow governments to reduce what they would have to spend on renewable energy and allocate funds to projects that can also have other positive externalities for society outside of producing clean electricity.

6.5.2 Regional pooling

Whether a public utility or a private company invests in renewables, the cost is initially passed on to consumers. For this reason, it is often in the consumer's best interest to resist energy transition policies. One of the ways consumers can benefit from an energy transition without electricity price increases is for producers to achieve better economies of scale. Our results seem to show that more populous provinces can attain a net-zero transition while spending a smaller proportion of their provincial GDP than less populous provinces. This could be the result of more attractive economies of scale for provinces that have to produce larger quantities of electricity. Thus, it is in the best interest of less populous provinces to pool their resources with other provinces or even US states in order to invest together in renewable energy infrastructures.

Further, additional inter-provincial transmission connections are shown to reduce generation capacity costs, reducing general decarbonization costs (Dolter and Rivers, 2018). To date, any transmission lines existing between provinces in Canada have been not been used to their full capacity. They have been used in what can be called "shallow integration", where energy trading is planned long ahead of time and no trading based on real-time electricity demand occurs. This makes building transmission lines much less appealing, since network flexibility is not enhanced. To achieve "deep integration", market conditions and regulation have to be the same from province to province (Pineau, 2012). Cost agreements also have to be reached between provinces as to which government or entity actually has to pay for the transmission lines. Building inter-provincial transmission lines has to be accompanied by a regional policy that creates a framework for power utilities in different provinces to coordinate their generation efforts. Regional policy of the sort could be the result of province-to-province dialogue. In Canada's political structure, federal guidelines could help create a framework to enhance economies of scale for less populous provinces. For trading with US states, common regional frameworks such as power pools could be implemented, but direct agreements between public utilities in a province and its neighbouring state remains the most effective, as that of Quebec with New York in 2021 for example. Such measures would reduce the general cost of the energy transition by improving economies of scale.

6.5.3 What role for the federal government?

Involving the federal government in provincial energy policy hasn't always been warmly welcomed. Canada's Constitution is interpreted as to include energy resources as being exclusively provincial jurisdiction. Policies enacted by the federal government have to garner the political support of all provinces for adherence to a pan-Canadian energy framework. However, this doesn't mean the federal government doesn't have a role to play in the country's energy transition.

6.5.3.1 Federal support to provincial projects

The Government of Canada has different means of providing financial resources to provinces for green energy projects. While many of the Government's projects address greener means of consuming electricity, such as initiatives to reduce the carbon footprint of public transit or newly constructed buildings, resources also exist to support the construction of green electricity infrastructures required for the type of energy transition accounted for in this study. Infrastructure Canada's "Investing in Canada Infrastructure Program – Green Infrastructure Stream" has the mandate to deliver funding to communities across Canada that want to invest in renewable energy infrastructures through cost-sharing agreements. Generation capacity improvements, large-scale battery storage, transmission lines or micro-grid implementation are some of the types of projects that the program sponsors. The department's "Smart Renewables and Electrification Pathways Program" also provides the possibility for funding for renewable energy generation capacity, notably solar photovoltaic, onshore wind or small hydroelectric projects, albeit for smaller scale projects in general. Both programs allow for and encourage partnerships with provincial and municipal governments. Created in 2017 as a way to stimulate private sector infrastructure growth, the Canada Infrastructure Bank (CIB) has also invested in energy storage and electricity generation projects. The Crown Corporation functions as a lender and investor to companies that want to undertake revenue-generating infrastructure projects.

As of 2021, the magnitude and the number of projects undertaken by Infrastructure Canada and the CIB are not at the level posited by our research to ensure a pan-Canadian energy transition. However, many projects that are being funded are directly connected to electricity storage, transmission or generation and the objectives of both organizations clearly include renewable electricity production as a priority. In financing a large-scale energy transition, the investment ecosystems provided by these organizations can be used to provide funding to provincial public utilities or private companies to stimulate renewable energy infrastructure development. Infrastructure Canada's programs currently seek to finance up to 50% of the cost of governmental provincial infrastructure projects it supports. These federal programs could best be applied to funding projects undertaken by provincial public utilities, with a higher participation percentage and a direct focus on green electricity production, transmission and storage. An enhanced scheme on the part of Infrastructure Canada for green energy would favour additional generation capacity in provinces that are largely hydro-dominated such as British Columbia or Quebec.

On the other hand, the CIB's framework could be used to stimulate renewable generation capacity growth in the private sector. By offering loans to private electricity companies at competitive rates specifically for the development of green electricity or by purchasing shares in future projects, the CIB could incentivize energy transition in provinces that do not adhere to a monopolistic public utility market structure, mostly provinces that produce electricity using fossil fuels such as Alberta or Nova Scotia. In line with our results, considering that the energy transition requires the largest amount of investment on the part of provinces that currently produce electricity using fossil fuels, the CIB could play a pivotal role in Canada's upcoming energy transition. CAD 35B are allocated to the organization for 2017-2028 for all projects in the organization's portfolio (Canadian Infrastructure Bank, 2019). Only a fraction of this budget is allocated to green energy projects. As shown in Table 6.A1, this is not nearly enough to cover the infrastructure costs of an energy transition in these provinces. For the CIB to play a role in Canada's energy transition, a program specifically designed for utilities to get support for renewables should be created with province-specific objectives and budgets. Further, the global annual budget of the CIB should be increased to get closer to the annual spending outlook from 2016 to 2060 outlined in Section 4.

6.5.3.2 Carbon pricing

More than half of Canada's provinces have implemented carbon pricing schemes, from carbon taxes, such as the point-of sale tax in British Columbia, to cap-and-trade agreements, such as in Quebec with California. In the context of an energy transition, carbon pricing is quite effective in promoting the construction of renewable electricity generation capacity by making fossil fuel generation capacity unaffordable. If achieving an energy transition is one of a province's goals, implementing a carbon pricing scheme would allow it to better reach net-zero. Each province should thus individually implement a carbon pricing scheme that can help achieve its transition targets. That being said, provincial carbon pricing initiatives are currently piecemeal and incohesive, seeking to attain different goals that depend on each province's citizens' political sympathy towards energy initiatives. Provinces that have already undergone an energy transition are much more sympathetic towards carbon pricing schemes, while provinces that still produce electricity through non-renewable means are more hostile. This isn't bewildering since carbon pricing in provinces that consume more fossil fuels entail large and rapid investments in renewables, making such policies economically unattractive. To date, provincial carbon pricing initiatives do not generate the required energy transition results Canada needs to reach net-zero.

More recently, the Government of Canada has announced a national carbon pricing scheme that will tax the price of a tonne of CO2 by CAD 170 by 2030. Provinces that do not implement themselves an equivalent carbon pricing scheme are forced to abide by the federal benchmarks. In principle, this is supposed to help Canada meet its 2030 emission targets and net-zero by 2050 (Langlois-Bertrand et al., 2021). However, given different provincial attitudes, the 2050 objective seems unrealistic. Further, it is not clear what will happen after 2030: will the carbon price keep going up? While an encouraging carbon pricing plan does exist in Canada, a more rigid framework to synchronize provincial initiatives should be put in place, and a carbon pricing scheme in line with the government's 2050 targets should be clearly enunciated. As shown in our model, higher fossil fuel prices result in more potential savings for provinces, in line with the hypothesis that carbon pricing would help stoke an energy transition. Our findings could be used as an argument to convince citizens of provinces that resist carbon pricing that in the long-run they will be the first to benefit from an energy transition. That being said, our results also show that a carbon tax is not necessary for all provinces to capture important fossil fuel savings that outpace initial investments.

6.5.3.3 A pan-Canadian electricity market?

Net-zero propositions for Canada include a large increase in electricity production in all provinces. In order to supply new end-use devices that would increasingly use electricity as a form of energy, namely with the widespread use of electric cars or electric home heating apparatuses, generation capacity has to be increased. Network integration across Canada could help increase the proportion of renewables used in provinces that mainly rely on fossil fuels for electricity production by allowing provinces that have large reserves of hydropower to sell their electricity to provinces who don't. There are compelling economic reasons that justify centralizing Canada's electricity production, with benefits such as less electricity consumption (De Villemeur and Pineau, 2012), heightened network efficiency (Pineau, 2013) or a faster decarbonization of energy systems (Dolter and Rivers, 2018). The integration of Canada's electricity market means more interconnections between provinces and enhanced energy flexibility for the country as a whole. By entrusting electricity production to one utility, economies of scale can be achieved at all levels of the organization, from the construction of larger dams with lower cost per kilowatt of capacity figures to savings on client-side operations. Further, utilities that are already specialized in electricity production through renewable sources have developed an expertise that utilities that produce electricity in thermal or nuclear plants do not possess.

However, integrating Canada's electricity market is not without challenges. Various obstacles have ostensibly limited Canada's ability to integrate its electricity system, and thus limited the potential for an energy transition through integration. Canada's multi-level governance system pins one province voters' interests against those of other provinces' voters (Pineau, 2012). Voters could perceive pan-Canadian integration as a loss of powers to the federal government or see it as a threat to the status quo in providing an essential service. Economies of scale procured by one province's state corporation do not directly benefit the other province's budget. Changing this multi-level governance system would possibly require a change of the country's constitution, an unlikely outcome to a very sensitive debate in Canadian politics. Sharing the costs enumerated in our results in Section 4 would also likely not be well received by provinces that require lower expenditures to reach net-zero.

The multi-level governance system in Canada, with each province using a different market structure, is partly to blame for different electricity prices from province to province. For instance, electricity in Saskatchewan is over double the price of electricity in Quebec. The price differences are especially palpable between traditional provinces and hydro-dominated provinces, where the citizens of provinces that mostly produce hydropower benefit on average from lower electricity prices (Joanis and Vaillancourt, 2020). Lower prices are partly because producing electricity using hydroelectric dams is cheaper than using thermal plants. Differing electricity prices from province to province are a barrier to national network integration since citizens of provinces that pay less for electricity have no incentive to open up to a market where they would end paying more per kilowatt-hour. A province that would save in fossil fuel costs more than another province would not be able to share those savings, even if the initial expenditures were shared.

A common benchmark electricity price fixed by a federal regulator could be a solution. By fixing a national electricity price for all Canadian provinces, citizens throughout Canada would all have the same power bill. This would give provinces an incentive to cooperate with each other to normalize their cost structures and in turn reduce some of the economic barriers to network integration. A common market would encourage inter-provincial transmission and would allow relatively smaller provinces to be able to benefit from larger clean energy infrastructures without the steep upfront costs. For example, Saskatchewan, which, according to our results, needs to invest more than 5% of its GDP in clean energy infrastructures for a number of years, could instead buy hydroelectricity using the benchmark price from neighbouring Manitoba, funding Manitoba's expansion of hydropower and transitioning without the hefty price tag. Lower fossil fuel consumption caused by further integration would also allow Saskatchewan and other fossil-fuel-consuming provinces to save on the cost of fuel to produce electricity.

Canada is fortunate to be a highly diversified economy with access to some of the world's largest supplies of natural resources. It is likely that Canada's primary sector could supply its industrial base to produce what is needed to implant the infrastructures required for an energy transition. In this sense, jobs created aside, investing in renewables could contribute to the growth of the Canadian economy and the economies of the provinces in which such infrastructures are built. However, this raises an important issue: provinces that currently produce fossil fuels will lose economic activity to provinces that would replace these sources of energy with renewables. All provinces would save on fossil fuel costs, but fossil fuel producing provinces would lose an important sector of their economies. To equitably integrate Canada's electricity network, transitory compensatory measures would have to be put into place to allow provinces that have large oil and gas sectors, such as Saskatchewan and Alberta, to pivot their economies towards new sources of income.

6.5.4 Conclusion

The Government of Canada has set a 2050 goal to reach a net-zero emissions target. An energy transition that replaces the use of fossil fuels by clean electricity is an indisputable part of any plan to reach that target. This cost-based analysis has attempted to quantify the economic feasibility of a pan-Canadian energy transition for each of Canada's ten provinces. We find that a complete energy transition towards a net-zero goal by 2045 is not prohibitively costly for any of the country's provinces. In fact, each province stands to benefit individually from the investment in renewable generation capacity due to the important fossil fuel savings incurred post-transition. The provinces that produce electricity using fossil fuels, namely Saskatchewan and Alberta, are those who will benefit the most economically from a pan-Canadian energy transition, while those who already produce electricity using renewable sources, namely British Columbia and Quebec, have less of an incentive to undergo a transition.

The differences between the provinces further support that evaluating energy transition costs and determining which policy pathways should be utilized must be done for each individual province as much as for Canada as a whole. A model based only on investment costs would probably deliver results that would show a transition costing a lot more in provinces using more fossil fuels for electricity generation due to a greater need for installing new generation capacity. Using a framework that analyzes a province's energy transition costs based solely on electricity production misses something that our model captures. This is because our model doesn't only take into account changes in electricity production, but also the reduction of fossil fuel consumption in other sectors. The declining use of fossil fuels is an inherent source of financial impetus to undergo the decarbonization of Canada's energy system, despite conservative figures for fossil fuel prices. Fossil fuel savings incurred by a transition are worth the preceding investments, even without the implementation of a carbon tax.

Making sure there are pathways towards sustainable investment in renewables paired with measures to facilitate market integration could very well be part of the solution to Canada's energy transition problem. Investing in renewables and their infrastructures must not increase the consumers' electricity prices. Federal investment funds can help provincial governments build these infrastructures. Stricter carbon pricing should make renewable generation capacity more appealing. Facilitating inter-provincial market integration will increase demand for clean energy from hydro-dominated provinces, an opportunity to sell electricity to provinces who will progressively be phasing out their thermal plants. These considerations will undoubtedly incentivize provinces that already possess renewable sources of electricity to invest in more generation capacity and allow them to benefit from better economies of scale.

Further research should set out to understand the impact of each of these proposed measures on the cost of an energy transition for Canada as a whole and each of the country's provinces. Limitations to this study include the use of Canada's nominal GDP for 2019 only and the lack of provisions made to account for fluctuations or changes to generation capacity costs or fossil fuel costs. Sensibility analyses or simulations of future prices and different GDP values could be included to better understand the permutations emanating from these variables. Indirect effects to the economy were not measured and labour market indicators were not considered. A more comprehensive economic model could be used in parallel to the model used in this paper as a source of complementary analyses. Costs related to electricity distribution infrastructure could also be included in further research. Finally, transmission and storage hypotheses were made using Heal's hypotheses (2020), based on the United States. An empirical study to determine Canada's specific storage and transmission needs in the event of a transition would improve the accuracy of our model.

CHAPITRE 7 ARTICLE 4: DECARBONIZING CANADA'S REMOTE MICROGRIDS

T. Stringer et M. Joanis ont écrit cet article. Celui-ci a été soumis en 2022 à la revue *The Energy Journal*.

7.1 Introduction

Canada produces most of its electricity using renewables, with some Canadian provinces, such as Quebec or Prince-Edward-Island, producing the quasi-totality of all their electricity renewably. However, because of the country's vastness and lack of infrastructure density, there are still a number of remote localities that depend on off-grid thermal plants to produce electricity using fossil fuels. Fossil fuel use is associated with spillage or leakage, leading to environmental risks. High levels of carbon emissions per capita are directly linked to electricity production in remote regions, with emissions coming from the transportation of the fuel as well as from its use in small-scale thermal plants (Arriaga et al., 2017). Moreover, the cost of producing electricity using fossil fuels in off-grid locations is far more expensive than in grid-connected locations. For example, Nunavut, a Canadian territory in which all electricity is produced using diesel generators, has residential electricity prices that are at least more than four times more expensive on average than those in Quebec (Canada Energy Regulator, 2017). In some communities, the price of electricity can be as high as nine times the Canadian average. This is because remote communities cannot access economies of scale the same way cities connected to North America's main grid can (Longo et al., 2019). These high electricity prices are detrimental to remote communities, as transport costs and high energy costs make it difficult for municipalities to offer reliable services and stimulate economic development (Robertson et al., 2020). Remote governments' budgets are weighed down by the cost of fuel impacted by high transport costs and suffer from instability due to the variation of fossil fuel prices on global markets (Jones et al., 2017). Citizens of remote communities also attribute a larger part of their income to electricity costs, which reduces their disposable income in a context where cost of living is already extremely high (Daley et al., 2015). Reducing electricity costs can help reduce poverty and better their quality of life. Part of reducing these costs is to reduce communities' dependency on fossil fuels – which is where a decarbonization would be beneficial.

In their analysis of the potential for different types of generation sources for microgrids in Canada's remote localities, Froese et al. (2020) conclude that clear economic benefits could be captured by moving from diesel to wind or solar. A transition to theses modes of electricity production requires significant investments, notably because of the energy storage costs that are required due to the variability and unreliability of solar panel and wind turbine electricity production. Even with decreasing battery costs, these costs remain substantial. More often than otherwise, remote communities in Canada have difficulty finding entities that are willing to invest in the start-up of renewable energy projects (Jones et al., 2017).

Renewable energy technology projects in Canada's remote communities are increasingly dependent on cooperation between different levels of government and remote communities' inhabitants (Karanasios and Parker, 2018). Local stakeholders want to know what kind of economic consequences implementing such projects will have on their communities. The economic effects of an energy transition from fossil fuels to renewables have been shown to be mostly positive, ranging from increases in productivity (Garcia-Casals et al., 2019; Nieto et al., 2020), lower electricity production costs (Kilickaplan et al., 2017) or job creation (Lehr et al., 2012). Assessing the cost of an energy transition is essential and has become the subject of a growing body of research and studies undertaken in many countries have shown that such a transition would not be overly costly. In Europe, annual expenditures to reach net-zero would be around 1% of GDP (Capros et al., 2014; D'Aprile et al., 2020) and would be economically and technologically feasible in the near future (Hainsch et al., 2021). In Germany, research shows that decarbonizing the electricity sector, had it been undertaken from 2017 on, would have cost 0.15% of the country's GDP (Unnerstall, 2017). In the United States, after deducting savings from fossil fuels that won't have to be consumed and savings from infrastructures that won't have to be replaced, a study came up with a figure of 0.02% of GDP for decarbonizing the electricity sector (Heal, 2020). In Canada, decarbonizing the electricity sector would fall somewhere between roughly 0.5% and 0.9% of GDP (Dolter and Rivers, 2018). Our previous research shows that reaching net-zero in Canada would cost between 1-3% of GDP over the next 30 years (Stringer et al. 2021). There is a high degree of variability between all of these values, namely because each country or region requires a costing model to be tweaked to the specifications of its geography and the specificities of its electricity sector. Many remote communities are located in Northern Canada and have different trends in terms of wind speed or solar irradiance than inhabited areas in Southern Canada. For this reason, further research pertaining to the unique challenges of decarbonizing remote microgrids is essential in implementing policies that promote the use of renewables.

To date, no study fully quantifies the cost of decarbonizing each of Canada’s remote communities’ microgrids or evaluates which technology would be the least costly for each community. Without this information, it is hard for governments and other stakeholders to get a sense of what kind of investments are needed. It is important to elucidate what the order of magnitude is for the costs of a decarbonization of microgrids in Canada’s remote localities. How much would it cost to decarbonize each of Canada’s remote community microgrids? Which electricity generation technology would be optimal for each of these communities? When would it be cheapest to implement this decarbonization? What policies are best to stimulate the implementation of these systems?

This paper uses the geographical, economic, energy and environmental data from Natural Resources Canada’s *Remote Communities Energy Database*, Natural Resources Canada’s *Photovoltaic Potential and Solar Resource Maps of Canada* and Environment and Climate Change Canada's *Wind Atlas* in an optimization model to determine the lowest possible cost of a renewable microgrid system for each of Canada’s remote settlements. Our study outlines which mode of electricity generation and which system rollout year are the best to minimize costs in each settlement of our data sample. Our results show that the total cost of decarbonizing remote microgrids is in line with previous research and that both solar panels and wind turbines should be used depending on the geographical characteristics of each settlement. We find that settlements that currently use diesel of heavy fuel to produce electricity should undergo a decarbonization as soon as possible, while those that use natural gas should wait until production and storage technologies become cheaper. We also find that waiting to decarbonize remote microgrids will favour the use of solar panels over wind turbines due to expected decreases in solar panel costs.

The rest of the paper is structured as follows. Section 2 outlines the empirical model we used. Section 3 describes the data we collected. Section 4 presents the study’s main findings. The final section discusses the policy implications of these results and concludes.

7.2 Model

The model that we use seeks the least costly permutation from the answers of three distinct and independent questions:

- Will electricity be generated using solar panels or wind turbines?
- Will energy be stored using lithium-ion or vanadium redox-flow batteries?
- In which year will the system be implanted in the settlement, 2020, 2030, 2040 or 2050?

Our previous research (Stringer et al., 2021) uses a cost estimation model to calculate the cost of an energy transition for all of Canada. It was itself based on Heal's (2020) decarbonization model for the United States electricity grid. We chose this approach because of its simplicity and effectiveness in offering a broad understanding of the costs incurred by decarbonization. The cost-based approach described in this section is similar to that used in these two prior studies. However, a decision model is also included in this study to determine if a solar or wind energy system is more advantageous. In prior research, various optimization models that select different technologies for a renewable energy system have been used to minimize costs or maximize revenue. A study focused on various locations in the province of Newfoundland-and-Labrador uses a simulation model (HOMER) to determine whether wind or solar microgrids are advantageous (Khan and Iqbal, 2005). Literature also shows the use of multiobjective optimization models (Valencia et al., 2019; Dong et al., 2021), linear optimization models (Crespo Montañés et al., 2021; Gorman et al., 2022) or binary integer programming (Khan et al, 2019). Because our research questions are binary in nature, binary integer programming can adequately model them.

We apply a cost-based binary integer optimization model to determine which mode of electricity production, which mode of energy storage and which year should be selected for each of the communities in our sample to convert an existing fossil fuel-based grid into a renewables-based one. We focus on community-level costs for each settlement. Thus, for each community, the model seeks to minimize the cost by evaluating which of the permutations as described by these three questions has the lowest dollar value. Each of these permutations is calculated using a cost-based approach that adds the generation capacity costs and the energy storage costs. Because the technologies cited above are set to decrease in cost over the next 30 years, a different cost for each of them is used for each system rollout year. Because the capacity factors for solar panels and wind turbines are different depending on the average wind speed and solar irradiance in the settlement's location, these variables were also taken into consideration. Fuel costs are also included in a second quasi-identical model to account for what would be spent on fuel if a transition to renewables is not undertaken. The base model examines the upfront costs needed to implant renewables in the settlements while the second seeks to understand what is gained by early adoption of renewables because of fossil fuel costs incurred in the future.

Wind turbines and solar panels were selected as the two generation options because other renewables such as hydro or geothermal require specific physical characteristics that cannot necessarily be found in all locations across Canada. Lithium-ion batteries were chosen as a first storage option because this technology is currently in use in the vast majority of grid-level battery storage (EESI, 2019). Vanadium redox-flow batteries[4] were chosen as a second option because they have proven to be the most interesting alternative to lithium-ion batteries for grid-level electrochemical battery storage, could become a competing technology with a large market share in the coming years and have the potential for seasonal storage (Arbabzadeh et al., 2015; Trovò, 2020).

7.2.1 The Base Model

The following model was applied to each settlement's annual electricity generation, average annual wind capacity factor and average annual solar capacity factor to calculate the infrastructure cost for each of the 16 permutations used to find the optimal solution. The total renewable energy system cost for a given settlement is obtained using the following equation:

$$C_{gst} = A_{gt} + B_{st} \tag{1}$$

where C_{gst} is the infrastructure cost for a mode of electricity generation g where g = 1,2 (Solar, Wind), type of storage system s where s = 1,2 (Lithium-ion, Vanadium Redox-Flow) and of system rollout year t where $t = 1,2,3,4$ (2020, 2030, 2040, 2050), A_{gt} is the cost of generation capacity for a mode of electricity generation g and system rollout year t, B_{st} is the cost of storage capacity for

[4] Redox-flow batteries "are electrochemical energy conversion devices, which exploit redox processes of species in solution in fluid form, stored in external tanks and introduced into the redux-flow battery when needed" (Alotto et al., 2014). Vanadium redox-flow batteries use vanadium as the solution used in these external tanks.

a mode of electricity storage s and system rollout year t. C_{gst} is the main cost parameter used in the optimization model. Its components are given using equations 2 and 3:

$$A_{gt} = \frac{u_{gt} \times Q}{\delta_g} \tag{2}$$

where u_{gt} is the cost of generation capacity by unit of energy (CAD/MWh) for a mode of electricity generation g and system rollout year t, Q is the quantity of fossil fuel energy consumed in one year to be replaced (MWh) in the settlement, δ_g is the capacity factor for a mode of electricity generation g for the settlement's geographical location. We chose to base our calculation of the electricity generation infrastructures on the electricity that was generated in one year rather than the installed capacity. This is because many settlements have far more generation capacity than they need to produce the amount of electricity they consume in one year, notably because of seasonal peak use and population changes. We estimate the lowest cost possible to achieve a system decarbonization, with the option of keeping existing thermal plants for peak use.

$$B_{st} = \frac{v_{st} \times Q}{365} \tag{3}$$

where v_{st} is the cost of storage capacity by unit of energy (CAD/MWh) for a type of storage system s and system rollout year t. B_{st} is the cost of the energy storage needed for one day of energy consumption in a settlement. The amount of storage needed can be amply debated, but for this study, 24 hours aptly covers most scheduled electricity shortages caused by the sun going down or low wind speed. Because of the unpredictability of the natural phenomena associated with these modes of electricity production, it is assumed that the grid's reliability will be ensured by conserving the existing thermal plants to shore up for any unplanned shortages. To this end, it is important to note that the microgrids will not be fully decarbonized and would effectively become hybrid microgrids.

The decision variable for the optimization model is expressed as x_{gst}, the choice of generation system g, of storage system s and of system rollout year t. It can be understood as a three-dimensional matrix that is populated by 16 binary variables.

The objective-function is expressed by:

$$\min \sum_{t=1}^{4} \sum_{s=1}^{2} \sum_{g=1}^{2} x_{gst} \times C_{gst} \tag{4}$$

Constrained by:

$$\sum_{t=1}^{4} \sum_{s=1}^{2} \sum_{g=1}^{2} x_{gst} = 1 \tag{5}$$

$$x_{gst} \in \{0,1\} \tag{6}$$

The model solves a minimization optimization problem where only one permutation of the decision variable can be equal to 1, thus selecting the value of C_{gst} that is the lowest.

7.2.2 Adding Fossil Fuel Costs

Fossil fuel costs are included in a second model in the form of an additional annual cost multiplied by the number of years between the time period of the permutation of the decision variable and 2020. It is computed as an opportunity cost incurred by not undergoing a grid decarbonization. The rationale behind including fuel costs lies in the fact that settlements that will not have undergone a transition towards renewables will still have to purchase the fuel necessary to produce the electricity they need. For 2030, 10 years of fuel consumption are added to the total cost; 20 years for 2040; 30 years for 2050. This also means that no additional fuel costs are added for 2020. The model used is quasi-identical to that above, with the addition of fossil fuel costs.

The following model was ran using each settlement's annual electricity generation, average annual wind capacity factor, average annual solar capacity factor and annual fuel cost to calculate the infrastructure cost for each of the 16 permutations used to find the optimal solution. The total renewable energy system cost with the inclusion of a fossil fuel opportunity cost for a given settlement is obtained using the following equation:

$$C'_{gst} = A_{gt} + B_{st} + F_t \tag{7}$$

where C'_{gst} is the total system cost for a mode of electricity generation g, type of storage system s and of system rollout year t, including fuel cost offsets, F_t is the additional cost of fossil fuels for all the years between 2020 and system rollout year t.

$$F_t = w \times Q \times (P_t - P_1) \tag{8}$$

where w is the cost by unit of energy (MWh) of the fossil fuel consumed in one year of electricity production in the community before a system rollout, P_t is the calendar year expressed by the system rollout year t (P_1 is 2020).

The decision variable x'_{gst} the choice of generation system g, of storage system s and of system rollout year t, when fuel cost offsets are taken into account. It is also expressed using a three-dimensional matrix that is populated by 16 binary variables.

The objective-function is expressed by:

$$\min \sum_{t=1}^{4} \sum_{s=1}^{2} \sum_{g=1}^{2} x'_{gst} \times C'_{gst} \tag{9}$$

Constrained by:

$$\sum_{t=1}^{4} \sum_{s=1}^{2} \sum_{g=1}^{2} x'_{gst} = 1 \tag{10}$$

$$x'_{gst} \in \{0,1\} \tag{11}$$

The cost per volume (CAD/liter) by settlement obtained in the *Remote Communities Energy Database* and the value of 38.68 GJ/m^3 (Dolter and Rivers, 2018) for existing thermal plants using diesel were used to calculate the fuel cost in CAD/MWh expressed by w. The same value was used to approximate fuel costs for the sole community using heavy fuel. To calculate de cost of natural gas, we use the Henry Hub average price for 2020, 2.13 USD/MMBtu (EIA, 2022), the USD to CAD average conversion rate for 2020 of 1.341 and the engineering conversion figure of 3.412 MMBtu per MWh. A value of 9.746 CAD/MWh was thus used.

7.2.3 Wind turbines and redox-flow batteries

We found that in all settlements, lithium-ion batteries were chosen by both optimization models for all time periods as they are cheaper for all time periods than vanadium redox-flow batteries. This isn't surprising considering lithium-ion batteries are currently the most produced form of electrochemical energy storage in the world. This begged the question as to whether the model was sensitive enough to the differences in generation intermittence typical of each mode of electricity production. Wind turbines are a reliable source of power generation and generally have higher capacity factors than solar panels. However, wind speed varies between days and has a less uniform distribution in any given month than solar irradiance (Ren et al., 2021). Batteries that can hold power for longer would be better suited in ensuring a more regular power supply from wind turbines to account for days where little electricity is produced. Vanadium redox-flow batteries can be used for longer-term power storage and seasonal demand while lithium-ion batteries cannot (Schmidt et al, 2019). For this reason, we also estimated a parallel scenario for both models, where wind turbines were paired only with vanadium redox-flow batteries and solar panels were paired only with lithium-ion batteries. This adds a constraint to the base model:

$$\sum_{t=1}^{4} x_{12t} + x_{21t} = 0 \tag{12}$$

and a constraint to the fossil fuel savings model:

$$\sum_{t=1}^{4} x'_{12t} + x'_{21t} = 0 \tag{13}$$

A discount rate was not used in this study. This is because the cost parameters used for storage and generation infrastructures already vary in time, and predict future costs in present value. We think these predictions are better than using discounted cash flows. Further, historical fossil fuel cost data shows upwards trends in the future, but are still subject to intense volatility due to shocks in the global oil and gas markets. An arbitrary discount rate does not capture these trends or risks. Four models in total were used with the data described in the following section. The base model, Model I, optimizes generation and storage costs, assuming all settlements use lithium-ion batteries. Model II optimizes generation and storage costs, assuming settlements attributed solar panels are fitted with lithium-ion storage and settlements attributed wind turbines are fitted with vanadium redox-flow storage. Model III optimizes generation, storage costs and fossil fuel savings, assuming all settlements use lithium-ion batteries. As the most comprehensive model, Model IV optimizes generation, storage costs and fossil fuel savings, assuming settlements attributed solar panels are fitted with lithium-ion storage and settlements attributed wind turbines are fitted with vanadium redox-flow storage.

7.3 Data and Descriptive Statistics

Three main data sources were used to compile information pertaining to the settlements in this study. Researchers at Statistics Canada have defined "settlements" as "tracts of land where humans have altered the physical environment by constructing residential, industrial, institutional and other installations or buildings" (Hofmann et al., 2010). For this study, we include all permanent residential settlements that have off-grid fossil fuel generation capacity. We use the Natural Resources Canada's *Remote Communities Energy Database* to select the list of settlements, electricity consumption, mode of electricity generation and fossil fuel price data, Natural Resources Canada's *Photovoltaic Potential and Solar Resource Maps of Canada* to obtain solar capacity factor data and Environment and Climate Change Canada's *Wind Atlas*' turbine formula to obtain wind capacity factor data. Cost parameters were obtained in prior literature.

7.3.1 The Settlements

Natural Resources Canada's *Remote Communities Energy Database* compiles all the electricity generation systems that are in place in Canada's remote areas. Natural Resources Canada offers a downloadable version of the full database on their website. The settlements that were chosen for this study were selected based on specific criteria that best answered our research objectives:

- Only settlements that are occupied by permanent communities were selected, i.e., no thermal plants that are specifically used for commercial purposes were included. While the transition to renewables is an important part of mining and other resource exploitation sites' path to sustainability, this study is meant to focus on the investments in renewables that would impact towns and municipalities where people are living permanently.

- Settlements were only selected if they were part of a multi-community local microgrid or were wholly off-grid. This is because communities that are connected to a larger main grid would undergo a transition that would impact a whole network, which would alter costs and make our study inaccurate for these communities.
- Only settlements in which the main power source is a fossil fuel were selected.
- Settlements in which there is no fossil fuel generating capacity were excluded.

For the 148 settlements that fit these specifications, the data for 11 variables (Community name, Province, Latitude, Longitude, Road access status, Fly-in status, Population count, Main power source, Annual fossil fuel generation in MWh/year, Price of fuel at site in CAD/liter) was collected. Road access status refers to if the settlement is connected by road to Canada's road network. Fly-in status refers to if the settlement is a fly-in community, meaning it is only accessible by airplane for most of the year.

7.3.2 Solar Data

Solar irradiance is the amount of solar energy received by a unit of area. Specific yield, expressed in kWh/kWp is a performance metric for a solar panel in a specific location. The annual average capacity factor of a solar panel system can be obtained by dividing the annual kWh/kWp value by the number of hours in a year. Natural Resources Canada's *Photovoltaic Potential and Solar Resource Maps of Canada* allows for a municipality search or a map search to find the annual specific yield values for a given location. We collected these values for each of the settlements and converted them to capacity factor measures. For settlements that did not appear in the database, we used the closest location with a similar latitude.

7.3.3 Wind Data

Environment and Climate Change Canada's *Wind Atlas* has a function that allows one to enter the coordinates (Latitude, Longitude) of a settlement to obtain the wind data specific to those coordinates. This tool also has a turbine formula that allows the user to enter the specifications of a wind turbine, namely cut-in speed and rated speed, to obtain the average annual capacity factor of that wind turbine in that location. We entered the coordinates for each of the settlements, followed by the values of 3.5 m/s for the cut-in speed and 14 m/s for the rated speed. These values correspond to median values found in a prior study (Dupont et al., 2018). We collected the returned annual capacity factor values for each of the settlements.

7.3.4 Cost parameters

Four technologies, two electricity generation technologies (wind and solar) and two storage technologies (lithium-ion and vanadium redox-flow), were evaluated in this study using infrastructure costs that decrease in time from 2020 to 2050. The costs for wind and solar generation technologies from 2020 to 2050 were retrieved in Canada's Energy Future 2020 (Canada Energy Regulator, 2020), as shown in Table 7.1. The costs for lithium-ion and vanadium redox-flow storage technologies in 2020 were taken from Mongird et al.'s previous work (2020). The costs for these storage technologies from 2030 to 2050 were extrapolated using Schmidt et al.'s (2019) cost predictions. These costs are shown in Table 7.2.

Table 7.1: Cost (in CAD) of electricity generation infrastructures to per MWh of annual production

u_{gt}	2020	2030	2040	2050
Solar Panels	9 908	7 770	5 694	4 117
Wind Turbines	9 075	8 935	8 742	8 199

Table 7.2: Cost (in CAD) of energy storage infrastructures per MWh of storage capacity

v_{st}	2020	2030	2040	2050
Lithium-ion Batteries	457 500	191 318	133 091	116 455
Vanadium Redox-Flow Batteries	498 750	264 643	193 393	173 036

Cost predictions in Tables 7.1 and 7.2 show interesting trends. Initially, solar panels are costlier than wind turbines, but experience substantial decreases in costs from 2020 to 2050. On the other hand, cost decreases for wind turbines are more modest. For both types of batteries, there are drastic cost reductions from 2020 to 2050, but lithium-ion batteries remain the cheapest during all periods.

7.3.5 Descriptive Statistics

Table 7.3 shows average values for the sample in the study for population count, annual fossil fuel consumption due to electricity production, price of diesel, latitude, solar and wind capacity factors. Population-wise, the sample is diverse, with the hamlet of Peace Point, AB with a population of 1, to Les Îles-de-la-Madeleine, QC with 12 475 inhabitants. Annual Fossil Fuel Consumption is highly correlated with population and has a similar variance. The price of diesel is also highly variable throughout the sample, with the community in which it is the most expensive paying close to 7 times what the community in which it is the cheapest is paying. This could be explained by differing transport costs, wholesale prices and government taxes or subsidies. The average latitude of the sample is 58.33 degrees, approximately that of Churchill, MB, meaning that the average off-grid settlement in Canada is very northernly. Solar capacity factors span an interval roughly five times smaller than that of wind capacity factors. The fact that there is such a high variability in capacity factors supports the development of a model that evaluates whether solar or wind generation capacity is adequate for each settlement.

Table 7.3: Population, Annual fossil fuel consumption, price of diesel and latitude statistics for all settlements in the sample

Variable	Mean	Min	Max
Population	811.80	1	12475
Annual Fossil Fuel Consumption (MWh/yr)	6141.43	52.29	181648
Price of Diesel (CAD/L)	1.04	0.35	2.36
Latitude (°)	58.33	47.26	76.42
Solar Capacity Factor	0.165	0.091	0.197
Wind Capacity Factor	0.282	0.048	0.574

Table 7.4 shows the breakdown of the settlements used in this by province or territory. Provinces or territories that don't have values entered do not have settlements included in the sample. Notably, the Maritimes do not have any off-grid communities. It is interesting to note that while Canada's northern territories represent 0.32% of the country's total population, their off-grid settlements represent 36% of the number of settlements and 43% of the total population in the sample. The totality of Nunavut's population, for example, is dependent on off-grid fossil fuel electricity generation. In Quebec and Newfoundland-and-Labrador, most of the off-grid

settlements in the sample are from Nunavik and Labrador, theses provinces' northernmost and remotest regions. As seen with the latitude values in Table 7.3, nordicity is correlated with off-grid electricity production.

Table 7.4: Number of settlements and population in sample by province or territory

Province/Territory	Number of settlements	Population in settlements
Alberta	5	5482
British Columbia	15	1836
Manitoba	5	3545
New Brunswick	-	-
Newfoundland-and-Labrador	20	6272
Northwest Territories	25	12 784
Nova Scotia	-	-
Nunavut	25	35 882
Ontario	29	19 297
Prince-Edward-Island	-	-
Quebec	20	29 831
Saskatchewan	-	-
Yukon	4	1159
Canada	**148**	**116 088**

Table 7.5 shows the number of settlements in the sample by various characteristics. Of all of the 148 off-grid settlements, 86% are indigenous communities, 73% have no year-round road access and 61% are fly-in communities. These statistics underline the disproportionate impact of the downsides of fossil fuel electricity production cited above on Canada's indigenous population. Further, a clear connection can be made between the lack of physical infrastructure and the use of off-grid electricity generation. High transport costs could be disincentivizing communities to invest in new modes of electricity generation and storage. The table also shows that over 97% of the off-grid communities in this study use diesel generators. This isn't surprising, since natural gas, the best fossil fuel alternative to diesel, needs to be transported to remote locations using specialized technology or a pipeline. Few locations in Canada are reached by a pipeline without being connected to their province's power grid. Without such infrastructure and given the long distances

separating remote communities from existing gas networks, liquefication would be the only viable mode of gas transportation. However, liquefying natural gas for transport and storage requires specialized technology and costly terminals.

Table 7.5: Count of settlements grouped by different characteristics

	Indigenous?		Year-round road access?		Fly-in?		Main fuel source		
	Yes	No	Yes	No	Yes	No	Diesel	Heavy Fuel Oil	Natural Gas
Number of settlements	128	20	40	108	91	57	144	1	3

7.4 Results

Table 7.A1 in the Appendix lists all the settlements in the sample we used for this study grouped by province and sorted from largest to smallest annual fossil fuel generation. It also incorporates the results from Model IV for each settlement, including the type of generation technology chosen, the year in which the optimal energy system solution would be deployed and the total cost corresponding to this solution. As described in the model description in Section 2, it is assumed that a settlement that is attributed “Wind” as generation mode is also attributed vanadium redox-flow batteries as its energy storage system, while a settlement that is attributed “Solar” is attributed lithium-ion batteries in this table. 78% of settlements are imputed a system rollout date of 2020 and 73% of them are attributed a wind turbine/redox-flow system. This is in line with the fact that in 2020, wind turbines are still cheaper than solar panels. It is interesting to note that the 15 communities in which it costs the most to convert to green generation sources represent 51% of the total costs and 53% of the total annual fossil fuel generation of all settlements. This means that if government stakeholders wanted to start by focusing on a few projects instead of all 148 settlements, they could target the ones with larger infrastructures to replace to maximize impact and reduce emissions quickly.

Table 7.6 summarizes results of our optimization models by showing the distribution of the number of photovoltaic and wind turbine systems among the 148 settlements in the sample for each model described in Section 2. It also shows the total cost associated with implanting the least costly energy system in each of the sample's settlements.

Table 7.6: Number of photovoltaic and wind turbine systems and cost breakdown for each optimization model (All cost figures expressed in millions of CAD)

	Number of settlements with photovoltaic systems	Number of settlements with wind turbine systems	A_{gt}	B_{st}	F_t	C_{gst} or C'_{gst}
I. Infrastructure Costs Model - Lithium-ion Storage	96	54	256	290	-	546
II. Infrastructure Costs Model - Lithium-ion and Redox-Flow Storage	143	5	269	319	-	588
III. Fossil Fuel Savings Model - Lithium-ion Storage	26	122	348	871	195	1,414
IV. Fossil Fuel Savings Model - Lithium-ion and Redox-Flow Storage	40	108	352	1,076	83	1,511

Only accounting for infrastructure costs incentivizes all settlements to wait until 2050 when generation and storage technologies are the cheapest. This explains the large discrepancies in costs between models I, II and models III, IV. This also has an impact on the choice of generation technology. As shown in Table 7.1, the cost of solar panels will decrease dramatically over the next 30 years. The same cannot be said about wind turbines, which drives the model to greatly favour solar panels for a transition in 2050. It can be noted that storage costs decrease dramatically between 2020 and 2050, explaining the 2x to 3x change in storage costs between models I, II and models III, IV.

Accounting for fossil fuel savings in the model makes it unfeasible to transition in 2050 for most settlements, with the quasi-totality attributed a transition year of 2020 or 2030. As seen in Table 7.A1, the only three settlements that are currently producing electricity using natural gas (Jasper, AB; Inuvik, NU; Norman Wells, NU) are slated to transition in 2050 using models III and IV. This is because electricity production using natural gas incurs far less important fossil fuel costs than electricity production using heavy oil or diesel. Choosing to include fossil fuel costs in the model fundamentally changes the transition strategy that each settlement will adopt in time. It also underlines to which extent fossil fuel consumption is costly to settlements that use petroleum-based energy sources as well as the urgency for these settlements to adopt greener sources of power.

Adding a constraint pairing solar panels to lithium-ion batteries and wind turbines to vanadium redox-flow batteries has two effects on the results. The first is that more settlements prefer solar panels, thus reducing the number of settlements using wind turbines. This is because redox-flow batteries are overall more expensive than lithium-ion ones, making the choice of solar panels with lithium-ion batteries more economically interesting for certain settlements. The second is that the generation capacity costs and especially storage costs see an increase. This underlines the importance of choosing energy storage technologies that are in line with means of electricity generation to better estimate system costs. This constraint also reduces the amount of extra fossil fuel costs. A big part of the shift from storage costs to fuel costs from Model III to Model IV is because the *Les Îles-de-la-Madeleine* settlement, the item in the whole sample with the highest total transition costs, pivots towards a 2020 transition date in Model IV. The shift is due to the fact that the decrease in storage costs between 2020 and 2030 associated with vanadium redox-flow battery technology is less important than the fossil fuel costs that would be incurred during this period, making it advantageous to transition earlier.

The stark differences in costs between models I, II and models III, IV illustrate how important fossil fuel costs are when estimating costs in the future. All four models yield total cost results that are in line or below cost estimates cited earlier in other literature. Model IV's CAD 1.5G figure is the largest of the four. Considering this sum would be spent over 30 years between 2020 and 2050, this would mean an annualized cost of CAD 50M for a population of around 116 000 in all 148 settlements. This roughly comes out to CAD 431 per person per year.

7.5 Conclusion and Policy Implications

Our paper addresses the geographical differences specific to remote communities and attributes a type of renewable generation technology to each settlement in our study. We examine Canada's remote settlements from an energy transition perspective comprehensively for the first time. Results in Section 4 show that the choice of renewable generation capacity technology is correlated with when the transition from fossil fuel generation to wind or solar occurs. If looking purely at infrastructure costs, waiting until 2050 for solar panels and battery storage to decrease in price allows settlements to have significantly less important costs. This also allocates solar panels rather than wind turbines as the least costly choice for the vast majority of communities. However, fossil fuel costs are an important factor in determining when a settlement is best positioned to undergo this transition. Accounting for them in two of our models showed that settlements would stand to benefit from transitioning in 2020 or 2030 rather than 2050 to be able to capture fossil fuel savings in subsequent years. These fossil fuel savings outweigh the decreases in generation and storage technology costs. An earlier transition also involves the construction of more wind turbines rather than solar panels because wind turbines are roughly the same price today as solar panels and have generally higher capacity factors. Expenditures are not overly costly and are in line with previous literature studying decarbonization.

Different stakeholders have a role to play in implanting these new systems in remote parts of Canada. Canadian provinces and territories have different electricity market structures ranging from public utilities that hold a monopoly on power generation, such as in Canada's territories, to competitive markets where regulated power pools are in place, such as in Ontario. In competitive markets, the private companies that service remote communities will have to invest in renewable microgrids. In provinces and territories where public utilities dominate the market, it will be up to provincial and territorial governments to invest in renewable energy microgrids. The impact of these investments on a government's budget depends on how much generation capacity has to be replaced. In this sense, it is easier for larger provinces to absorb transition costs in their remote communities than territories in which a large share of electricity production is fossil-fuel driven. In populous provinces such as Quebec or British-Columbia, the net effect on public utility budgets wouldn't be that important. Public utilities in less populous political entities don't necessarily have the liquidity to fund new investments. Canada's territories, representing 43% of the population in the sample for this study, experience this problem acutely.

For example, Nunavut's public utility, Qulliq Energy, initiated a feasibility study in 2005 for a hydroelectric project to supply Iqualuit with clean energy. On its own, Iqualuit's power consumption accounts for close to a third of the total consumption in the territory and over 6% of total remote electricity consumption of all settlements in the sample used in this study. Unfortunately, the project was cancelled due to lack of funding opportunities and was shelved indefinitely (Qulliq Energy Corp., 2016). The only way to fund a new project for a public utility of an entity of this population size is to raise electricity prices or additionally strain the government's budget. Considering that the price of electricity is already extremely high in remote localities in Canada's territories (Canada Energy Regulator, 2017) and that higher taxes on some of the country's most impoverished communities would be detrimental to quality of life, funding could come from external sources.

The federal government can support provincial and especially territorial projects by offering financial resources to public and private utilities. Programs that are set up to decarbonize Canada's electricity market by cost-sharing with other levels of government do exist. Infrastructure Canada already has two programs in place, "Investing in Canada Infrastructure Program – Green Infrastructure Stream" and "Smart Renewables and Electrification Pathways Program". Crown-Indigenous Relations and Northern Affairs Canada has the "Northern REACHE (Northern Responsible Energy Approach for Community Heat and Electricity) Program". Only the REACHE program specifically addresses challenges related to remote renewable electricity projects. Nonetheless, the sums allocated in the 2017 budget for this program were of CAD 53.5M over ten years. This is most probably not enough to ensure the decarbonization of Canada's northern settlements. Funds from Infrastructure Canada's programs could be allocated to REACHE to centralize resources and robustly tackle renewable remote electrification. The Canadian Infrastructure Bank (CIB), another entity of the federal government, functions as a lender or investor to companies that want to undertake infrastructure projects. Private utilities that service remote communities could benefit from the CIB's framework to obtain the liquidity needed to invest in microgrids. Many of the projects for which funds were invested or lent are large-scale. A subsidiary of the CIB could pointedly address the particularities of small-scale electrification projects to better help private utilities.

For utilities that are able to ensure the liquidity levels necessary for decarbonization efforts in remote settlements, certain projects could be prioritized more than others. First, settlements that use natural gas for electricity production should consider waiting before a transition since their fossil fuel savings are less interesting. Second, governments could focus on larger settlements rather than smaller ones to be able to benefit from economies of scale in the installation of new infrastructures. As mentioned in Section 4, the top 10% of all the settlements in the sample represent over half of the total decarbonization infrastructure costs. To get the ball rolling, pre-feasibility studies for these settlements could be rapidly ordered. Third, settlements that are fly-in are best positioned for savings by being prioritized. Their fuel costs are systematically higher than non-fly-in settlements due to increased transport costs, which means they have more savings to capture by transitioning early. A large fly-in settlement that uses diesel for power generation such as Iqualuit fits this description.

Further research should set out to understand which modes of financing are the most effective in incentivizing utilities to invest in renewable microgrids. Limitations to this study include the fact that annual averages were used in lieu of month-specific values for wind and solar capacity factors. There is a certain degree of uncertainty concerning the future cost of generation and storage technologies. The same goes for fuel costs, which are heavily dependent on global markets and could decrease drastically for remote communities as new road, rail and gas infrastructures are built in Northern Canada. Hydroelectricity or tidal power were not considered for any of the settlements. Finally, hypotheses pertaining to grid-scale batteries were made to evaluate short to medium-term energy storage. Research that incorporates more modes of electricity production, better technology and fuel cost predictions and more granular wind speed and solar irradiance data would refine our analysis greatly.

CHAPITRE 8

CHAPITRE 8 DISCUSSION GÉNÉRALE

La problématique abordée dans cette thèse est celle des coûts engendrés par la construction d'infrastructures dans le Nord du Canada et des bénéfices sociaux et économiques qui peuvent être captés par la suite.

Cette problématique a été explorée de par différents angles afin de donner lieu à quatre contributions distinctes. La première est une étude comparative entre les phases de développement d'infrastructures dans le Nord du Québec et le projet du Corridor nordique canadien qui trouve qu'un corridor nordique n'est pas forcément idéal. La seconde est une évaluation statistique des impacts de la construction de routes dans le Nord du Québec et au Labrador qui montre que la connexion routière a des effets socio-économiques positifs. La troisième compare les coûts engendrés par chaque province pour une transition énergétique au Canada, détermine que cette transition est abordable et propose des pistes de politiques publiques pour y arriver. La quatrième explore les coûts associés à la décarbonisation de micro réseaux électriques en régions éloignées et détermine que le choix de technologies de production d'énergie dépend des changements en coûts dans le temps. Chaque contribution est unique et répond à des questions de recherche qui n'ont pas été posées auparavant. L'intersection entre la nordicité et les infrastructures est peu étudiée malgré son importance capitale dans le contexte canadien.

Les articles reprennent plusieurs thèmes en commun et se sont succédés logiquement au fur et à mesure que la recherche a été entreprise. La première contribution utilise le Québec comme cas pour comprendre le développement historique d'infrastructures dans le Nord et les raisons qui ont généré ce développement. La deuxième contribution est axée sur les villages nordiques, reprend une partie des données collectées lors de la première et utilise des méthodes statistiques pour comprendre ce qui change dans les communautés connectées par des routes nordiques. La troisième contribution se centre de nouveau sur le développement d'infrastructures pancanadien, mais cette fois dans une perspective de coûts liés à la décarbonisation et d'énergie renouvelable. La quatrième contribution utilise un modèle très similaire à celui utilisé dans la troisième, mais cette fois avec modèle d'optimisation. Les conclusions de chaque paire d'articles permettent une ouverture vers d'autres sujets dans une optique de continuité de la recherche.

8.1 Considérations méthodologiques

Les deuxième et quatrième contributions utilisent toutes les deux le concept de la « communauté » ou de la « municipalité » pour analyser des enjeux liés aux infrastructures. Dans beaucoup de littérature, le Nord est abordé comme un monolithe qui ne varie que très peu d’un endroit à un autre. Utiliser les particularités des communautés qui peuplent cette région du Canada permet de mieux comprendre ce qui différencie certaines communautés de d’autres. De plus, dans le contexte de ces deux contributions, la construction de routes et la décarbonisation sont toutes les deux présentées comme des facteurs qui peuvent améliorer la qualité de vie des habitants de ces communautés. Il est possible même que la construction de routes facilitera la décarbonisation des micro réseaux électriques. Cette synergie mérite qu’on s’y penche davantage dans des études futures.

Les première et troisième contributions complémentent l’aspect quantitatif des autres parties de la thèse en ajoutant une perspective de politique publique à l’analyse. Cependant, les conclusions des deux articles ne se rejoignent pas complètement et illustrent la différence entre la construction routière et la production d’électricité. Dans le premier article, le non-sens du tracé du Corridor nordique canadien est expliqué en montrant que, géographiquement, celui-ci n’est pas en accordance avec les phases de développement précédentes au Québec et le nombre de kilomètres de nouvelles infrastructures à construire est prohibitif. Bien que l’autonomie du Québec soit soulevée, l’utilité d’un tel corridor est surtout mise en question pour des raisons physiques. À l’opposé, dans le troisième article de cette thèse, l’intégration du réseau électrique à l’échelle du pays est proposée comme une solution pour une imminente transition énergétique. Le principal obstacle à cette intégration est politique pour des raisons constitutionnelles. La juridiction provinciale de l’énergie est indiscutable actuellement au Canada. Ces deux conclusions pourraient faire l’objet de deux thèses à leur tour. Or, cette différence entre les articles exhibe la complexité du fonctionnement du fédéralisme canadien et comment la taille du pays peut être une entrave à sa centralisation.

8.2 Le Nord

Les première, deuxième et quatrième contributions arrivent à des conclusions intéressantes quant au développement d’infrastructures propres au Nord. La littérature existante concernant la construction d’infrastructures routières ou en énergie renouvelables montre des effets globalement positifs. Nous pouvons extraire des conclusions semblables de cette thèse. La deuxième contribution montre que le chômage baisse et le niveau d’éducation augmente avec la connexion routière. La quatrième contribution montre que des investissements relativement modestes génèrent des économies en coûts en énergie fossile intéressantes. La première contribution présente un point de vue moins catégorique quant à la construction de nouvelles infrastructures et suggère qu’il est important de tenir en compte les intentions derrières le développement historique du Nord. Bien que banal en surface, cette thèse affirme que l’accès routier, la décarbonisation et une bonne planification d’infrastructures sont importants. Le développement du Nord passe inévitablement par la construction d’infrastructures. Seulement, il faut que ce développement se fasse en concertation avec les intérêts des communautés nordiques plus que malgré eux. Les modalités de cette concertation sont à déterminer à l’avenir de façon plus concrète.

La spécificité de cette étude est que les conclusions quant aux bienfaits des infrastructures proviennent trop souvent d’études qui utilisent des contextes très différents du contexte nordique canadien, avec des régions plus peuplées. Par exemple, dans la première contribution, l’énormité des distances change la façon de concevoir l’analyse. Dans la seconde, le fait de tout simplement connecter un village éloigné à l’écoumène du Sud du Canada, quelque chose qui est souvent pris pour acquis en régions plus densément peuplées, a un réel impact socio-économique. Dans la quatrième, l’irradiance solaire, moins importante en régions nordiques, a un impact sur le modèle de coûts. Ces exemples et biens d’autres indiquent que la nordicité devrait elle-même constituer un facteur dans des études portant sur le nord. Il est possible qu’un biais existe dans la littérature, et que celle-ci soit foncièrement basée sur la perception venant d’un monde où quasiment toutes les institutions de recherche se trouvent dans des régions plus densément peuplées que les régions nordiques.

Les deux premières contributions se basent largement sur l’histoire du développement d’infrastructures dans le Nord du Québec et au Labrador. L’élément partagé par ces deux articles qui saute aux yeux est que le développement d’infrastructures nordiques est chose récente, soit dans les 70 dernière années. Ceci explique le peu de littérature existante au sujet de ces infrastructures, mais souligne également l’aspect évolutif de ce que nous concevons comme étant le Nord. Les mêmes méthodes d’analyse utilisées dans 70 ans vont sans aucun doute nous donner des résultats complètement altérés et mettre de l’emphase sur des enjeux différents. Avec une plus grande densité d’infrastructures, la pertinence de la nordicité sera peut-être remise en question. Les articles portant sur des régions plus peuplées seront potentiellement plus justes dans l’analyse des régions nordiques du Canada, et la recherche future devra considérer cette évolution.

8.3 Transition énergétique

Du côté transition énergétique, les deux dernières contributions nous amènent à des conclusions semblables, soit que la décarbonisation ne soit pas trop coûteuse pour un pays comme le Canada. Il ressort de ces conclusions que les provinces et villages éloignés qui dépensent le plus en énergies fossiles ont le plus grand intérêt à entreprendre la décarbonisation de leur électricité. Se départir d’énergies fossiles est potentiellement libre de coûts trop élevés et comporte même des avantages économiques. Dans une économie où l’industrie pétrolière demeure une force majeure, la réalité qui transparaît dans ces contributions doit être contrebalancée d’un plan pour remplacer ce secteur de l’économie. Bien que l’investissement en énergie renouvelable puisse agir comme solution partielle à ce problème, c’est une opportunité pour diversifier davantage l’économie canadienne et sans doute écrire un autre article.

Un thème qui ressort de la concaténation des résultats du deuxième article et des infrastructures des troisième et quatrième articles est celui de l’impact socio-économique des investissement en capacité de production d’électricité. De la même façon que la construction d’une route peut avoir un impact socio-économique positif qui va plus loin que la réduction en coûts de transport, la construction d’éolienne et de panneaux solaires en régions éloignées, accroissant l’autonomie énergétique des communautés concernées, peut également apporter des effets bénéfiques à une communauté qui vont plus loin que les enjeux énergétiques. La méthode utilisée dans le cadre du deuxième article peut être appliquée à d’autres types d’infrastructure sans grande modification, telles que celles présentées comme des solutions à une transition énergétique dans les deuxième et troisième articles. Peu de projets de micro-réseaux d’électricité renouvelables existent au Canada, mais il y en a potentiellement assez pour collecter les données nécessaires pour un échantillon dans le cadre d’une étude exploratoire. Création d’emploi, meilleurs salaires et réduction du coût de la vie font partie des différents effets qui pourraient avoir lieu de par l’entrée d’un nouveau micro-réseau hybride ou entièrement renouvelable. Un modèle qui tient en compte à la fois des liens routiers et des micro-réseaux hybrides pourrait également servir à mieux comprendre les interactions entre ces deux types d’infrastructure.

Bien que les interactions entre les infrastructures routières et les infrastructures énergétiques dans le Nord ne sont pas encore connues en détail, certaines synergies entre elles sont fort probablement perceptibles, bien qu'elles n'aient pas été mesurées dans le cadre de cette thèse. D'abord, tel qu'observé dans le quatrième article, les communautés nordiques qui ont une connexion routière bénéficient de coûts de carburant plus bas. Ces coûts plus bas, ironiquement, poussent ces communautés à moins favoriser une transition énergétique dans le modèle utilisé dans cette thèse. Or, un aspect qui n'est pas quantifié est celui des coûts de transport liés à l'acheminement des infrastructures énergétiques en régions éloignées, notamment celles de production d'électricité comme des panneaux solaires ou des éoliennes, ou celles de stockage comme des batteries à grande échelle. Il est fort possible que la réduction de ces coûts parfois prohibitifs pousserait les communautés dans la direction d'une transition énergétique. Il serait particulièrement intéressant d'explorer comment l'accès routier a permis ou facilité des projets de micro-réseaux hybrides par le passé. En parallèle, en utilisant un modèle de régression qui trace les effets socio-économiques des deux types d'infrastructures, il sera possible de décerner s'il y a une valeur ajoutée à la construction des deux types d'infrastructures en même temps qui est supérieure à l'addition de l'effet mesuré pour une route et l'effet mesuré d'un micro-réseau.

8.4 Les investissements publics

Les résultats des troisième et quatrième articles suggèrent qu'une des manières les plus importantes de financer une transition énergétique est d'inclure une part significative de fonds publics. La comparaison dans le premier article concernant le Corridor nordique canadien met en garde le lecteur des dangers d'un financement public mal dirigé, notamment dans le contexte de projets purement extractifs. D'une part, elle fait mention des projets miniers des années 1950 qui n'ont pas cherché à assurer la pérennité de communautés nordiques, laissant parfois des villes fantômes suite à la fin de la période d'exploitation d'une mine. D'autre part, elle cite l'échec de certains partenariats public-privé dans le cadre du Plan Nord, où le Gouvernement du Québec a dû financer des projets qui ont été abandonnées par des entreprises privées. Une transition énergétique qui sera largement financée par des fonds publics en concertation avec des intérêts privés devra se doter de mécanismes pour éviter les erreurs du passé en ce qui concerne les infrastructures de transport.

Par ailleurs, les routes sont largement financées par des intérêts publics au Canada. Différents paliers de gouvernement acceptent d'investir de larges sommes pour atteindre différents objectifs avec un nouveau lien routier. Dans le cadre du développement du Nord au Québec, des objectifs traditionnellement extractifs ont été favorisés. Plusieurs infrastructures, notamment les chemins de fer qui desservent la faille du Labrador, ont été construites dans le but spécifique de créer une mine et pouvoir l'exploiter. Le fait même de prendre la décision d'investir dans un projet minier à un lieu ponctuel a des conséquences économiques en soi. Ceci signifie que les effets socio-économiques qui seront mesurées en utilisant un modèle de régression doivent contrôler les conséquences de cette décision. L'utilisation d'un modèle des doubles différences agit comme précaution à un certain niveau pour ce genre de biais en contrôlant pour certaines caractéristiques immobiles dans le temps des municipalités de l'échantillon. Cependant, ceci ne contrôle pas, par exemple, les effets de la création d'un projet minier pendant les années de l'étude. Deux contrôles additionnels pourraient être ajoutés au modèle, notamment celui de si un projet économique d'envergure a été inauguré à proximité d'une municipalité et celui du niveau d'investissement public par capita pour une municipalité ou une région géographique donnée.

CHAPITRE 9 CONCLUSIONS ET RECOMMANDATIONS

Cette thèse explore différents enjeux propres au Nord du Canada et aux infrastructures. Peu ou pas de littérature touchant à l'impact économique de routes sur des communautés nordiques existe. Il en est de même pour les coûts associés à la décarbonisation de leurs micro réseaux électriques. Pour remplir ces lacunes dans la recherche existante, quatre articles ont été rédigés et consistent de quatre contributions uniques. Ce chapitre résumera les limites de chacune d'entre elles et des recommandations pour de la recherche future.

La première contribution regroupe les développements des infrastructures du Québec en trois phases principales, synthétise chaque phase et les compare de manière critique au Corridor nordique canadien. Toute proposition concrète de développement d'infrastructures dans le nord du Québec doit tenir compte de l'histoire politique de la province et des motivations derrière les développements d'infrastructures antérieurs. Cette histoire politique comprend la relation entre le Québec et le fédéralisme canadien, qui a été le moteur du développement des infrastructures pancanadiennes dans le passé. Des études d'impact sur l'environnement doivent être réalisées pour assurer l'intégrité écologique de la nature sauvage et pulvérulente du Québec. Enfin, les communautés autochtones dont les terres seraient affectées par la construction d'infrastructures résultant du concept du corridor nord doivent être consultées de manière approfondie et avoir la possibilité de participer à toutes les étapes du projet de développement.

La deuxième contribution utilise des données de recensement du nord du Québec et du Labrador pour évaluer les effets de la connexion routière sur les municipalités connectées entre 1986 et 2016. Les limites de la deuxième contribution incluent l'omission d'estimer d'autres variables indépendantes qui pourraient potentiellement servir d'indicateurs supplémentaires de certains phénomènes évoqués plus haut, le manque de points de comparaison internationaux et le faible nombre d'observations. La recherche future pourrait englober des analyses avec d'autres variables pour mieux comprendre l'effet de la connexion routière sur le développement des municipalités éloignées. Notamment, des données sur la mobilité pourraient être collectées pour mieux comprendre le nombre de personnes entrant ou sortant des communes desservies par la route, confirmant éventuellement l'hypothèse selon laquelle une meilleure adéquation spatiale de la main-d'œuvre est à l'origine de la baisse observée des taux de chômage. Il pourrait également être utilisé pour comprendre le flux de résidents qui quittent les municipalités pour obtenir de meilleurs diplômes. Des données sur les taux de pauvreté pourraient être collectées pour aider à obtenir une image plus claire de l'impact réel sur la réduction de la pauvreté que les résultats de cette étude peuvent entraîner. Des méthodes similaires utilisant des municipalités d'autres pays avec des variables identiques permettraient également de déterminer si les effets étudiés dans cet article sont uniques au Canada ou s'ils sont omniprésents dans le monde. Enfin, du fait de la taille modeste des échantillons utilisés, les conclusions de cet article doivent être appréhendées avec prudence. Des tailles d'échantillon plus grandes et des périodes de temps plus longues augmenteraient le pouvoir prédictif du modèle mathématique et éviteraient les différences de résultats lors de l'utilisation de méthodes d'estimation d'erreur standard robustes.

La troisième contribution utilise des données de simulation de consommation d'énergie et un modèle de calcul des coûts pour évaluer les dépenses d'infrastructure pour une transition net-zéro pour chacune des dix provinces du pays d'ici 2060. De futures études devraient viser à comprendre l'impact de chacune de ces mesures proposées sur le coût d'une transition énergétique pour l'ensemble du Canada et chacune des provinces du pays. Les limites de cette étude comprennent l'utilisation du PIB nominal du Canada pour 2019 seulement et l'absence de provisions pour tenir compte des fluctuations ou des changements des coûts de la capacité de production ou des coûts des combustibles fossiles. Des analyses de sensibilité ou des simulations de prix futurs et de différentes valeurs de PIB pourraient être incluses pour mieux comprendre les permutations émanant de ces variables. Les effets indirects sur l'économie n'ont pas été mesurés et les indicateurs du marché du travail n'ont pas été pris en compte. Un modèle économique plus complet pourrait être utilisé parallèlement au modèle utilisé dans cet article comme source d'analyses complémentaires. Les coûts liés à l'infrastructure de distribution d'électricité pourraient également être inclus dans d'autres recherches. Enfin, des hypothèses de transmission et de stockage ont été faites à partir des hypothèses de Heal (2020), basées sur les États-Unis. Une étude empirique pour déterminer les besoins spécifiques de stockage et de transport du Canada en cas de transition améliorerait la précision de notre modèle.

La dernière contribution utilise une approche basée sur les coûts avec un modèle d'optimisation à nombres entiers binaire pour trouver la solution de décarbonation la moins coûteuse pour chaque communauté éloignée d'ici 2050. Des recherches supplémentaires devraient viser à comprendre quels modes de financement sont les plus efficaces pour inciter les services publics à investir dans les micro-réseaux renouvelables. Les limites de cette étude comprennent le fait que des moyennes annuelles ont été utilisées au lieu de valeurs mensuelles spécifiques pour les facteurs de capacité éolienne et solaire. Il existe un certain degré d'incertitude concernant le coût futur des technologies de production et de stockage. Il en va de même pour les coûts du carburant, qui dépendent fortement des marchés mondiaux et pourraient diminuer considérablement pour les collectivités éloignées à mesure que de nouvelles infrastructures routières, ferroviaires et gazières sont construites dans le Nord canadien. L'hydroélectricité ou l'énergie marémotrice n'ont été envisagées pour aucune des communautés. Enfin, des hypothèses relatives aux batteries à l'échelle du réseau ont été posées pour évaluer le stockage d'énergie à court et moyen terme. Des études intégrant davantage de modes de production d'électricité, de meilleures prévisions en matière de technologie et de coût du carburant et des données plus granulaires pour la vitesse du vent et l'irradiance solaire affineraient considérablement l’analyse.

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ANNEXE A CARTES DU CHAPITRE 4

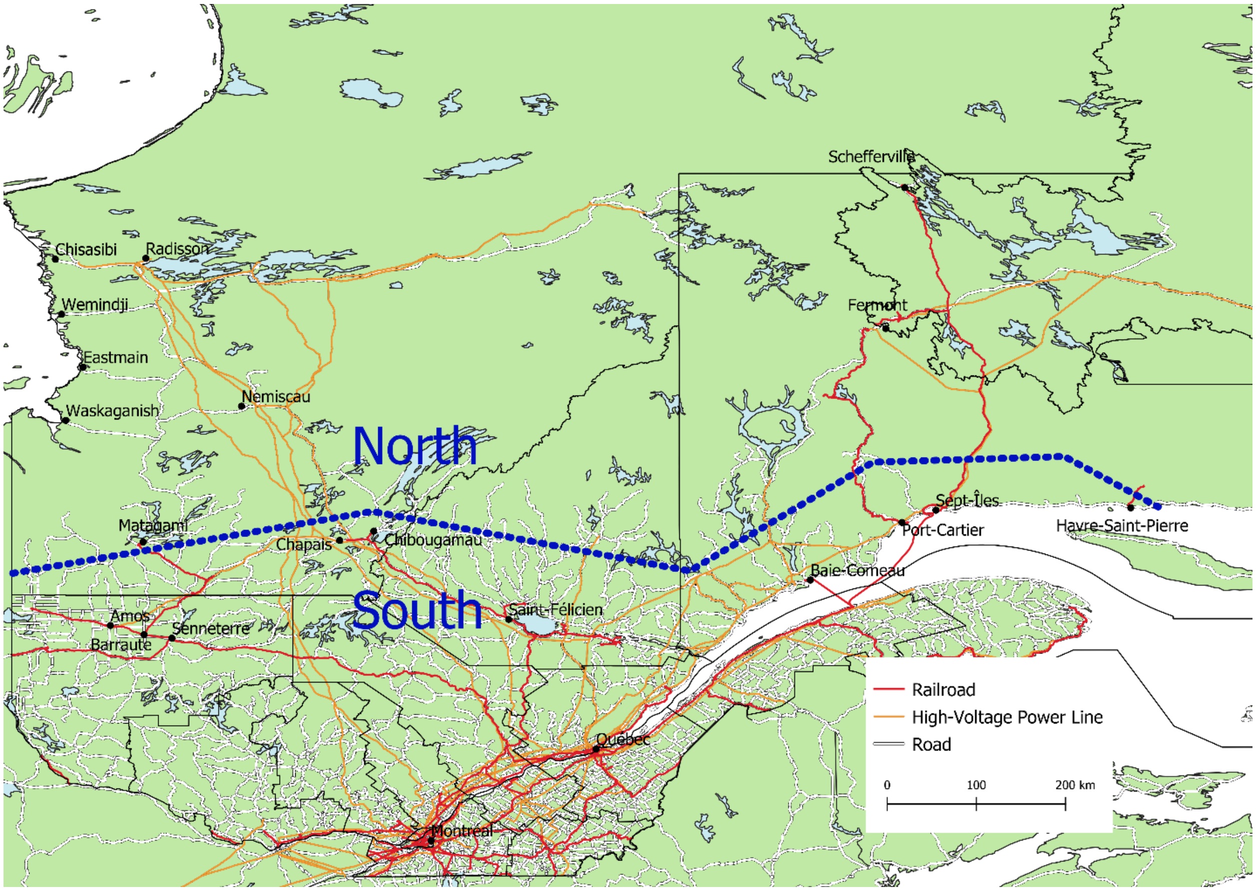

Figure 4.1 : Map of existing infrastructures in Northern Quebec with the delimitation of the “North” as per Hamelin’s 200 VAPO bound

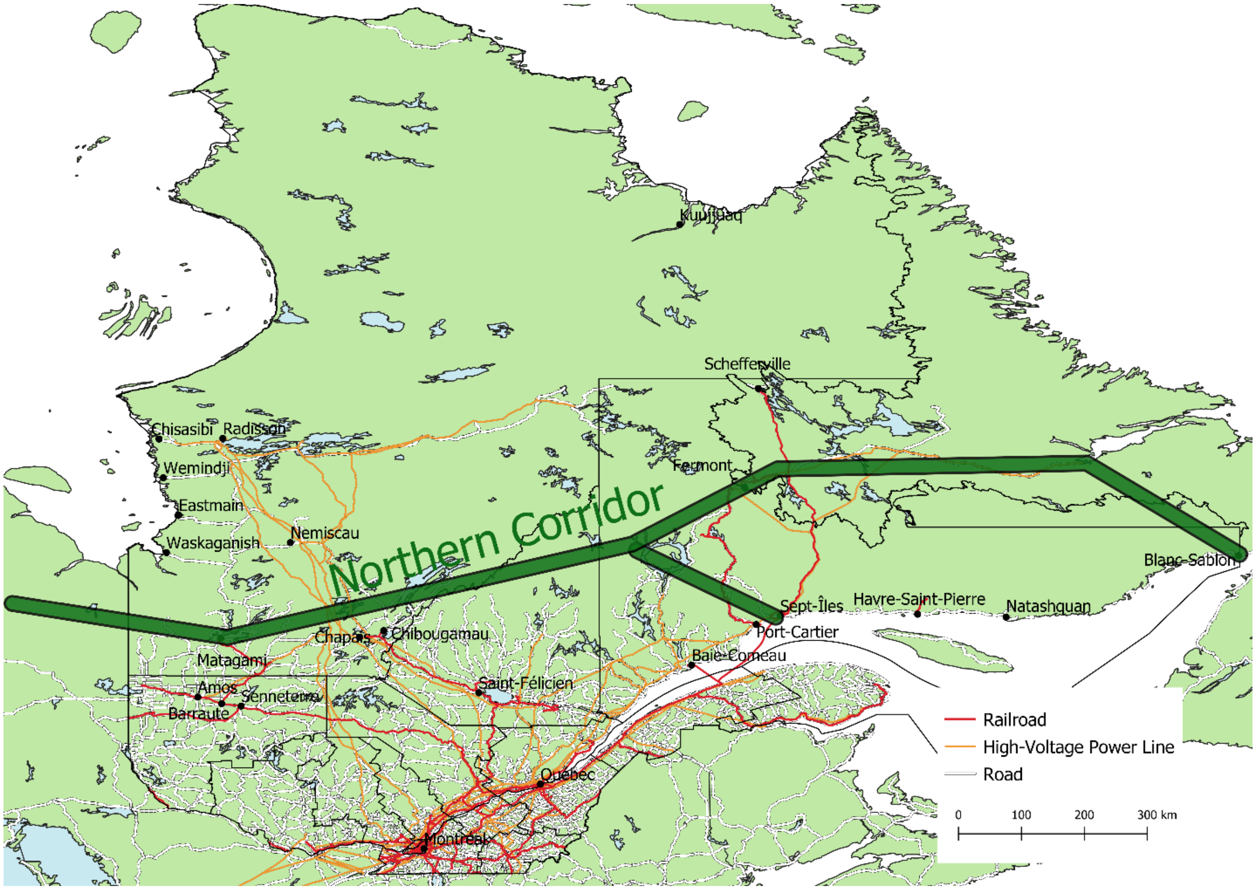

Figure 4.2 : Map of existing infrastructures in Northern Quebec and the preliminary outline of the Canadian Northern Corridor Concept

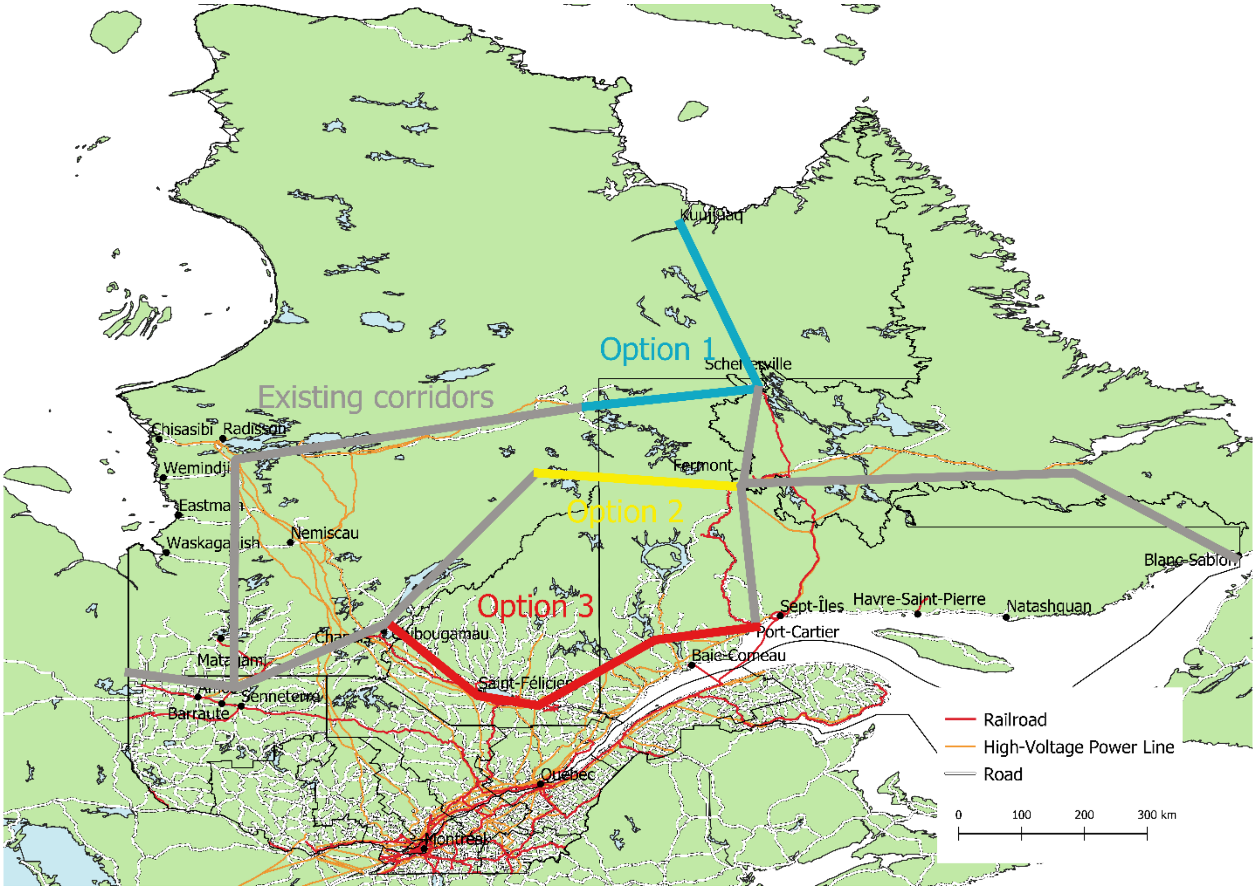

Figure 4.3 : Map of existing infrastructures in Northern Quebec and three potential options for the Canadian Northern Corridor Concept

ANNEXE B FIGURES ET TABLEAUX DU CHAPITRE 5

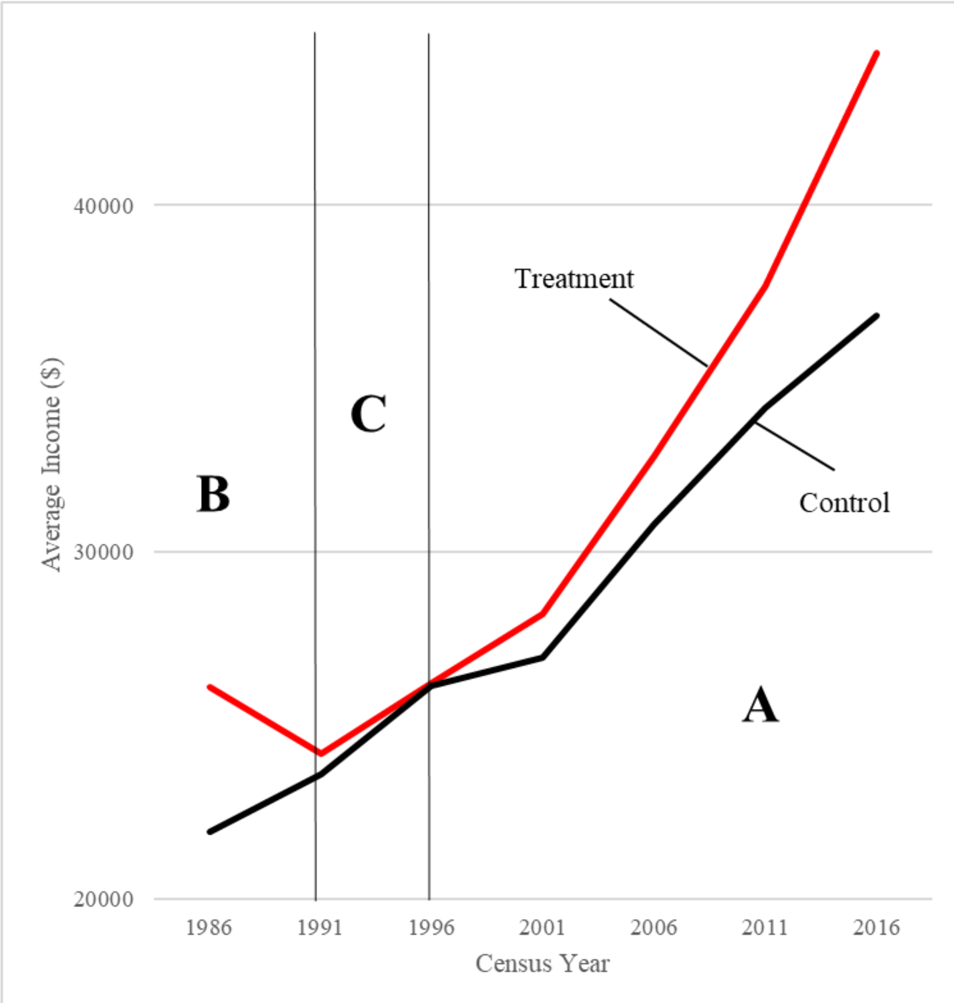

Figure 5.1 : Average income of municipalities by year; control group vs. treatment group with road constructed between 1991 and 1996

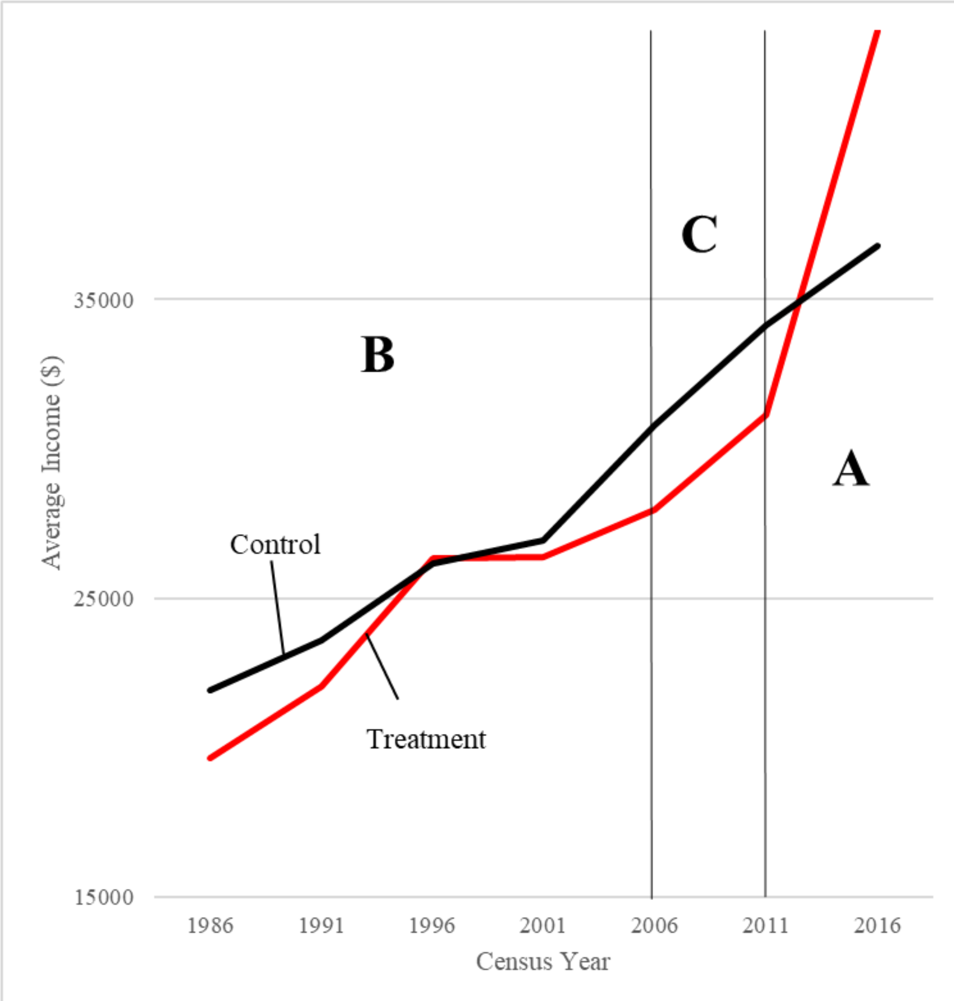

Figure 5.2 : Figure 2: Average income of municipalities by year; control group vs. treatment group with road constructed between 2006 and 2011

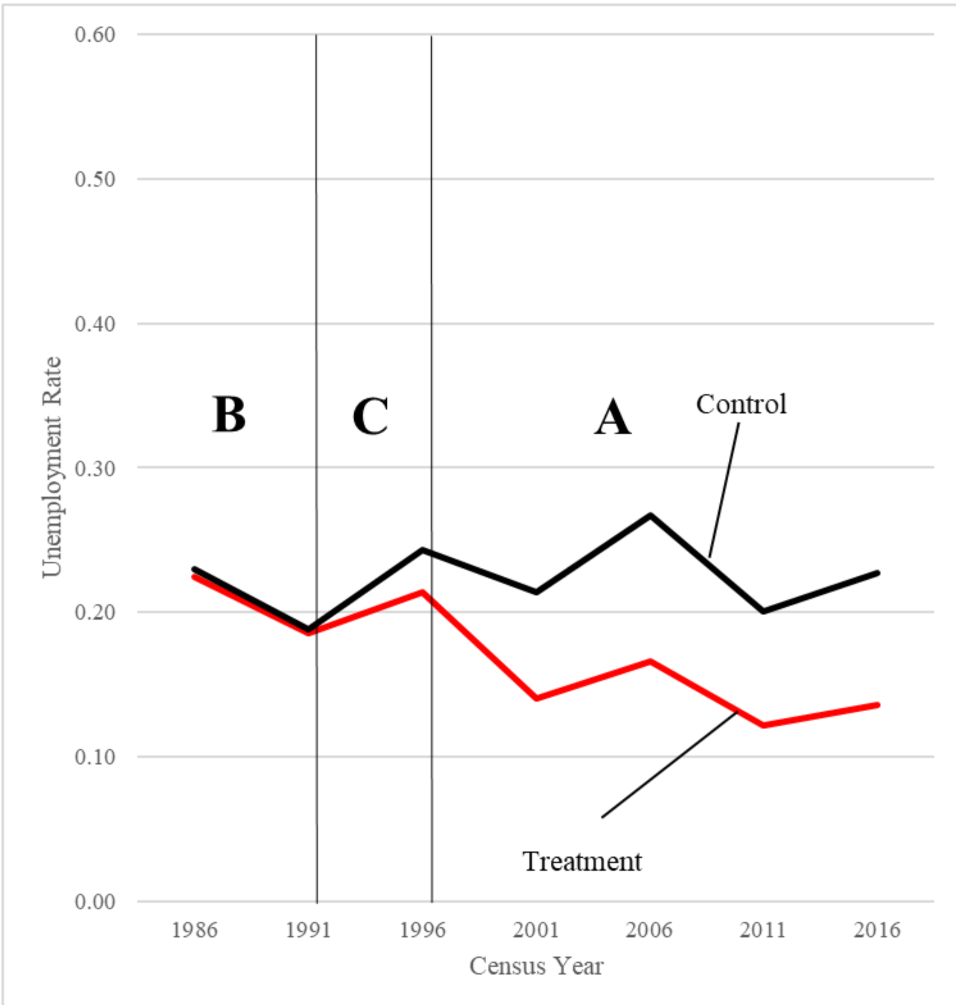

Figure 5.3 : Unemployment rate of municipalities by year; control group vs. treatment group with road constructed between 1991 and 1996

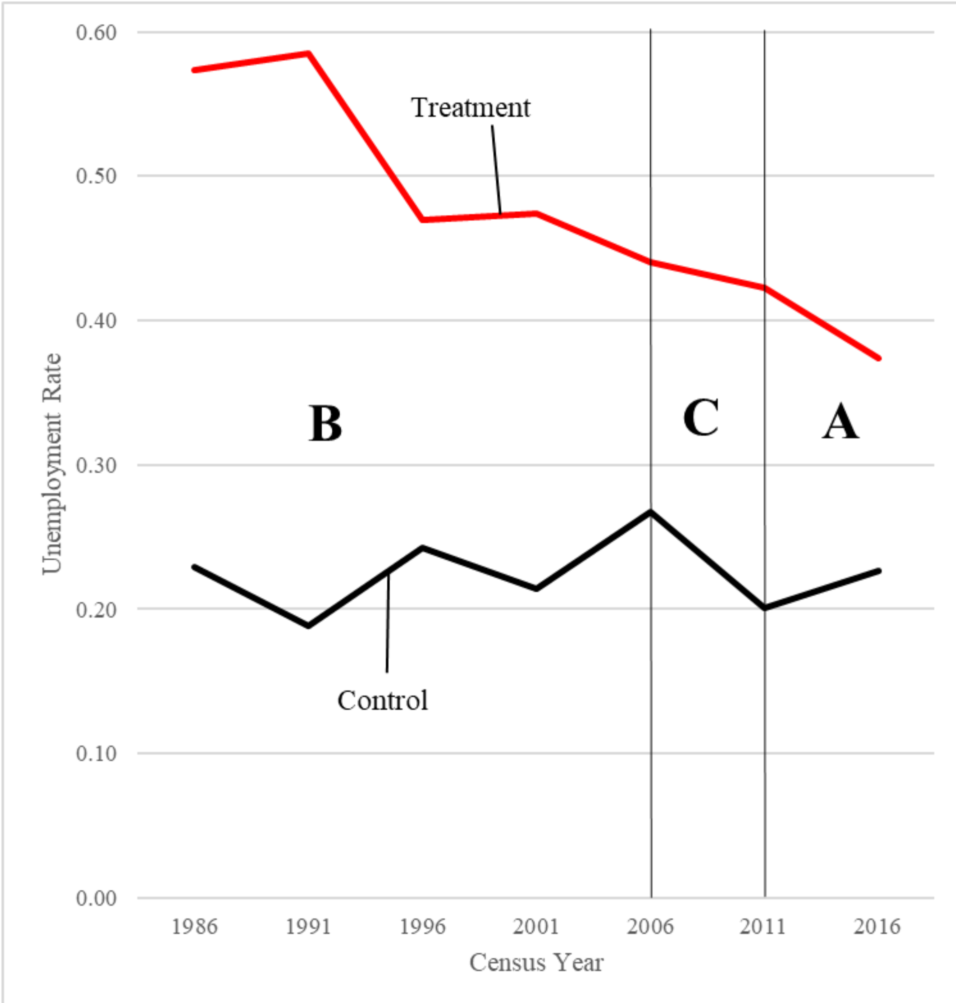

Figure 5.4 : Unemployment rate of municipalities by year; control group vs. treatment group with road constructed between 2006 and 2011

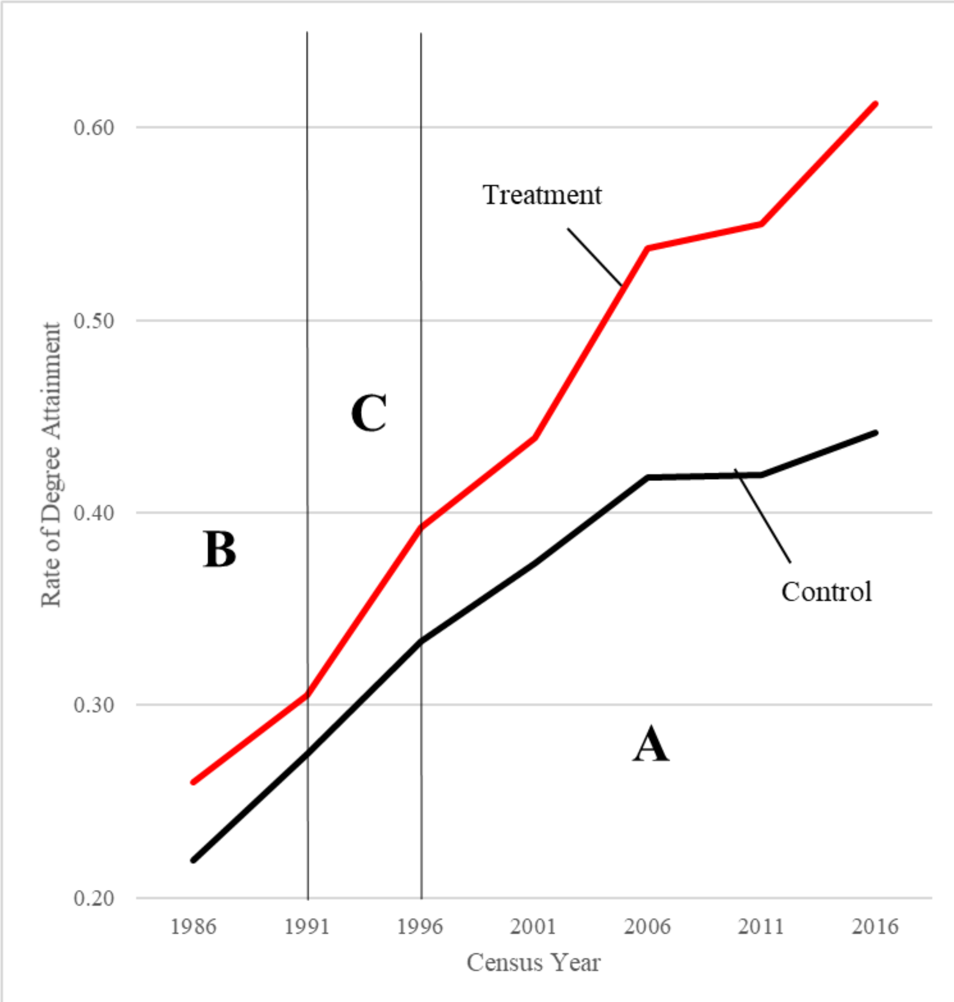

Figure 5.5 : Rate of degree attainment of municipalities by year; control group vs. treatment group with road constructed between 1991 and 1996

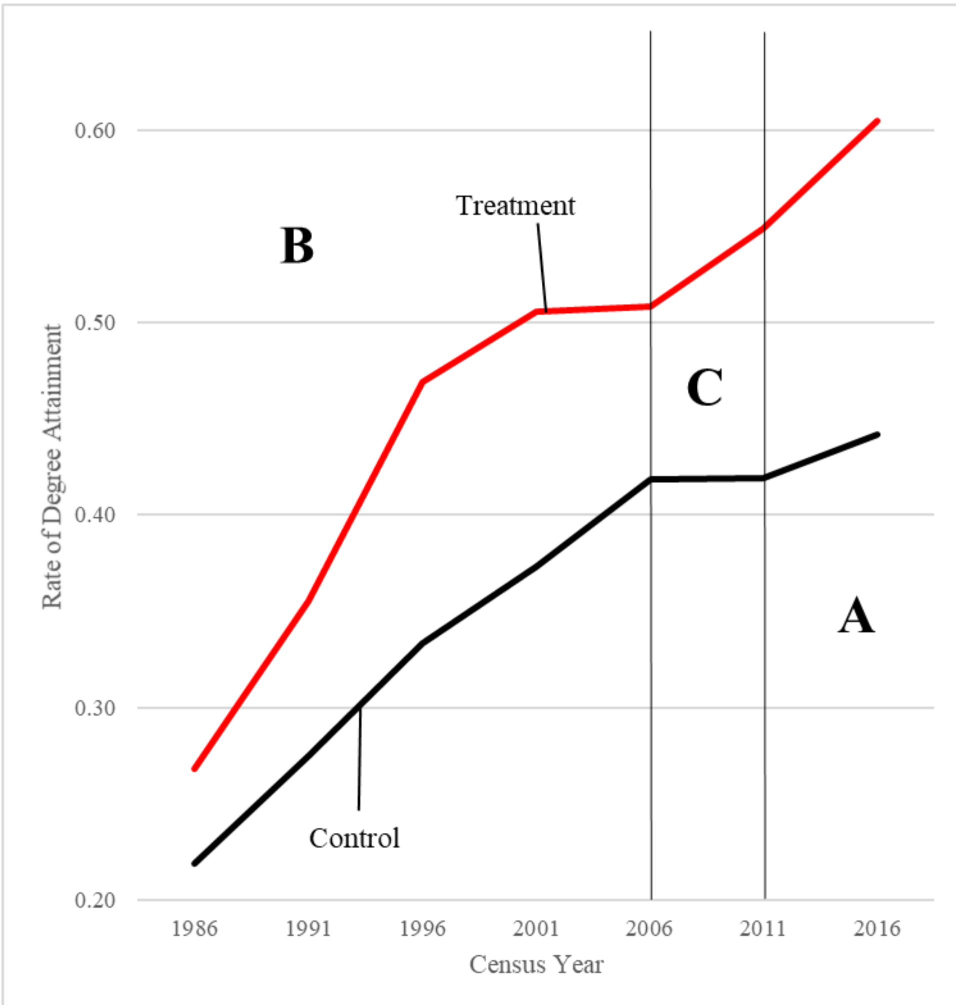

Figure 5.6 : Rate of degree attainment of municipalities by year; control group vs. treatment group with road constructed between 2006 and 2011

Table 5.A1 : Results on Average Income

	(1)	(2)	(3)	(4)	(5)	(6)
Road Connection	6402.81***	1872.59*	10454.35***	1513.26*	1429.16*	1429.16
	(1175.31)	(994.90)	(1179.67)	(803.57)	(798.42)	(1609.25)
Proportion of Indigenous Inhabitants					3581.68**	3581.68**
					(1755.40)	(1459.22)
Number of observations	249	249	249	249	249	249
R-squared overall	0.1073	0.465	0.1073	0.4644	0.3951	0.3951
R-squared within			0.2741	0.7761	0.7806	0.7806
Year fixed effects	No	Yes	No	Yes	Yes	Yes
Municipality fixed effects	No	No	Yes	Yes	Yes	Yes
Covariates	No	No	No	No	Yes	Yes
Robust standard error (Driscoll-Kraay)	No	No	No	No	No	Yes

*: p < 10%; **: p < 5%; ***: p < 1%

Table 5.A2 : Results on Unemployment Rate

	(1)	(2)	(3)	(4)	(5)	(6)
Road Connection	-0.0435*	-0.0331	-0.0799***	-0.0699***	-0.0599***	-0.0599**
	(0.0248)	(0.0270)	(0.0174)	(0.0209)	(0.0207)	(0.0221)
Proportion of Indigenous Inhabitants					-0.133***	-0.133***
					(0.0455)	(0.0274)
Aggregate Income (per billion $)					-0.0527	-0.0527
					(0.456)	(0.0882)
Number of observations	249	249	249	249	249	249
R-squared overall	0.0121	0.027	0.0121	0.0186	0.2277	0.2277
R-squared within			0.0902	0.109	0.1559	0.1559
Year fixed effects	No	Yes	No	Yes	Yes	Yes
Municipality fixed effects	No	No	Yes	Yes	Yes	Yes
Covariates	No	No	No	No	Yes	Yes
Robust standard error (Driscoll-Kraay)	No	No	No	No	No	Yes

*: p < 10%; **: p < 5%; ***: p < 1%

Table 5.A3: Results on Employment Rate

	(1)	(2)	(3)	(4)	(5)	(6)
Road Connection	0.0407*	0.00254	0.0856***	0.0135	0.0132	0.0132*
	(0.0212)	(0.0221)	(0.0155)	(0.151)	(0.0152)	(0.00626)
Proportion of Indigenous Inhabitants					-0.0806**	-0.0806*
					(0.0335)	(0.0398)
Aggregate Income (per billion $)					-0.0954	-0.0954
					(0.336)	(0.0751)
Number of observations	249	249	249	249	249	249
R-squared overall	0.0145	0.106	0.0145	0.1031	0.0495	0.0495
R-squared within			0.1258	0.4367	0.4407	0.4407
Year fixed effects	No	Yes	No	Yes	Yes	Yes
Municipality fixed effects	No	No	Yes	Yes	Yes	Yes
Covariates	No	No	No	No	Yes	Yes
Robust standard error (Driscoll-Kraay)	No	No	No	No	No	Yes

*: p < 10%; **: p < 5%; ***: p < 1%

Table 5.A4 : Results on Participation Rate

	(1)	(2)	(3)	(4)	(5)	(6)
Road Connection	0.0100	-0.0262	0.0413**	-0.0307	-0.0273	-0.0273
	(0.0182)	(0.0185)	(0.0194)	(0.0205)	(0.0198)	(0.0266)
Proportion of Indigenous Inhabitants					-0.209***	-0.209**
					(0.0435)	(0.0592)
Aggregate Income (per billion $)					-0.219	-0.219***
					(0.437)	(0.0519)
Number of observations	249	249	249	249	249	249
R-squared overall	0.0012	0.1369	0.0012	0.1361	0.2029	0.2029
R-squared within			0.0209	0.255	0.3185	0.3185
Year fixed effects	No	Yes	No	Yes	Yes	Yes
Municipality fixed effects	No	No	Yes	Yes	Yes	Yes
Covariates	No	No	No	No	Yes	Yes
Robust standard error (Driscoll-Kraay)	No	No	No	No	No	Yes

*: p < 10%; **: p < 5%; ***: p < 1%

Table 5.A5: Results on Rate of Degree Attainment

	(1)	(2)	(3)	(4)	(5)	(6)
Road Connection	0.161***	0.100***	0.184***	0.0483***	0.0378**	0.0378**
	(0.0218)	(0.0209)	(0.0205)	(0.0158)	(0.0154)	(0.0149)
Proportion of Indigenous Inhabitants					0.0758**	0.0758**
					(0.034)	(0.0234)
Aggregate Income (per billion $)					0.246	0.246
					(0.341)	(0.327)
Number of observations	249	249	249	249	249	249
R-squared overall	0.1787	0.3723	0.1787	0.3562	0.2613	0.2613
R-squared within			0.2763	0.7052	0.7323	0.7323
Year fixed effects	No	Yes	No	Yes	Yes	Yes
Municipality fixed effects	No	No	Yes	Yes	Yes	Yes
Covariates	No	No	No	No	Yes	Yes
Robust standard error (Driscoll-Kraay)	No	No	No	No	No	Yes

*: p < 10%; **: p < 5%; ***: p < 1%

Table 5.A6: Results on Total Population

	(1)	(2)	(3)	(4)	(5)	(6)
Road Connection	689.71***	718.68***	81.83*	-110.47**	-95.20**	-95.20
	(191.01)	(209.12)	(41.87)	(43.65)	(40.59)	(54.70)
Proportion of Indigenous Inhabitants					-524.99***	-524.99**
					(89.80)	(139.98)
Number of observations	249	249	249	249	249	249
R-squared overall	0.0494	0.0507	0.0494	0.0004	0.0201	0.0201
R-squared within			0.0177	0.2728	0.3768	0.3768
Year fixed effects	No	Yes	No	Yes	Yes	Yes
Municipality fixed effects	No	No	Yes	Yes	Yes	Yes
Covariates	No	No	No	No	Yes	Yes
Robust standard error (Driscoll-Kraay)	No	No	No	No	No	Yes

*: p < 10%; **: p < 5%; ***: p < 1%

ANNEXE C TABLEAUX SUPPLÉMENTAIRES DU CHAPITRE 6

Table 6.A1: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs, by province, time period and scenario (CAD millions)

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Alberta	2016-2030	825	2,015	899	1,463	1,909	825	2,015	899	1,463	1,909	0	0	0	0	0
	2030-2040	1,078	1,836	1,336	1,293	1,958	91	1,836	3,486	4,878	5,892	988	-1	-2,150	-3,585	-3,934
	2040-2050	1,260	1,240	-61	-1,126	-4,101	-32	1,242	3,311	3,297	2,210	1,292	-2	-3,372	-4,423	-6,311
	2050-2060	1,178	595	-2,598	-5,436	-5,658	-121	242	1,391	385	268	1,299	353	-3,990	-5,821	-5,926
	2060+	895	-258	-5,083	-5,175	-4,905	0	0	0	0	0	895	-258	-5,083	-5,175	-4,905
British Columbia	2016-2030	1,006	1,025	1,027	1,339	1,694	1,006	1,025	1,027	1,339	1,694	0	0	0	0	0
	2030-2040	1,168	581	1,774	1,647	2,575	213	215	1,412	1,724	2,768	954	366	363	-77	-192
	2040-2050	1,220	648	1,869	2,147	1,399	137	382	2,283	3,031	2,733	1,083	266	-413	-884	-1,334
	2050-2060	1,065	730	1,018	-203	-444	-97	120	1,741	1,214	555	1,161	610	-722	-1,417	-999
	2060+	1,345	740	-1,326	-1,330	-824	0	0	0	0	0	1,345	740	-1,326	-1,330	-824
Manitoba	2016-2030	571	572	571	574	589	571	572	571	574	589	0	0	0	0	0
	2030-2040	547	1,194	703	857	1,284	8	867	341	773	1,250	539	326	362	84	34
	2040-2050	689	642	944	681	-213	-7	535	846	902	534	696	107	98	-220	-747
	2050-2060	1,079	265	577	-465	-500	77	315	596	316	251	1,002	-50	-18	-781	-751
	2060+	1,272	-38	-643	-679	-640	0	0	0	0	0	1,272	-38	-643	-679	-640
New Brunswick	2016-2030	63	245	182	283	410	63	245	182	283	410	0	0	0	0	0
	2030-2040	-331	-336	74	93	-112	37	261	442	538	576	-369	-597	-368	-444	-688
	2040-2050	-468	-514	-353	-624	-747	-189	105	205	197	243	-280	-619	-558	-821	-990
	2050-2060	-9	-455	-454	-718	-766	147	140	251	150	100	-156	-595	-705	-868	-866
	2060+	-160	-591	-783	-753	-755	0	0	0	0	0	-160	-591	-783	-753	-755
Newfoundland-and-Labrador	2016-2030	328	404	418	921	927	328	404	418	921	927	0	0	0	0	0
	2030-2040	-181	-239	428	314	273	308	361	1,029	1,010	1,012	-489	-599	-601	-696	-739
	2040-2050	-177	-288	-387	-742	-803	340	347	325	3	-3	-517	-635	-713	-745	-801
	2050-2060	-117	-234	-617	-733	-648	323	295	1	0	0	-440	-529	-618	-734	-648
	2060+	-417	-472	-572	-552	-565	0	0	0	0	0	-417	-472	-572	-552	-565

Table 6.A1: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs, by province, time period and scenario (CAD millions) (Continued)

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Nova Scotia	2016-2030	70	103	37	96	260	70	103	37	96	260	0	0	0	0	0
	2030-2040	345	297	443	298	252	29	-23	333	325	286	316	320	109	-28	-34
	2040-2050	258	199	-89	-177	-306	3	0	177	279	339	256	199	-266	-456	-644
	2050-2060	172	105	-107	-683	-601	-16	-24	287	-50	-12	187	129	-395	-632	-589
	2060+	185	128	-544	-564	-524	0	0	0	0	0	185	128	-544	-564	-524
Ontario	2016-2030	-526	2,252	1,456	3,190	3,832	-526	2,252	1,456	3,190	3,832	0	0	0	0	0
	2030-2040	4,218	5,407	6,678	6,064	7,113	674	3,769	5,080	6,359	7,744	3,544	1,638	1,598	-295	-631
	2040-2050	5,309	5,738	5,977	3,536	-610	1,118	4,503	6,512	7,344	5,556	4,191	1,235	-535	-3,809	-6,166
	2050-2060	3,173	1,056	295	-4,730	-4,870	-2,056	1,803	3,306	1,303	1,263	5,228	-747	-3,011	-6,033	-6,133
	2060+	6,938	-1,233	-5,114	-5,480	-5,333	0	0	0	0	0	6,938	-1,233	-5,114	-5,480	-5,333
Prince-Edward-Island	2016-2030	27	40	32	48	53	27	40	32	48	53	0	0	0	0	0
	2030-2040	11	21	39	13	-4	-2	39	50	63	52	13	-18	-11	-50	-56
	2040-2050	-18	-69	-31	-77	-117	-22	-3	34	21	24	4	-66	-66	-98	-140
	2050-2060	16	-81	-64	-106	-104	5	-11	15	13	13	11	-70	-79	-118	-117
	2060+	21	-66	-103	-107	-99	0	0	0	0	0	21	-66	-103	-107	-99
Quebec	2016-2030	573	2,316	597	597	672	573	2,316	597	597	672	0	0	0	0	0
	2030-2040	309	553	1,113	1,731	3,023	521	1,662	1,941	3,356	4,763	-212	-1,109	-828	-1,625	-1,741
	2040-2050	588	-778	-200	-1,374	-2,653	692	298	1,517	1,628	1,652	-104	-1,076	-1,717	-3,002	-4,305
	2050-2060	210	-433	-208	-2,306	-2,542	59	520	1,873	1,212	851	152	-953	-2,081	-3,518	-3,394
	2060+	479	-1,103	-2,883	-3,064	-2,794	0	0	0	0	0	479	-1,103	-2,883	-3,064	-2,794
Saskatchewan	2016-2030	-6	442	160	231	582	-6	442	160	231	582	0	0	0	0	0
	2030-2040	634	981	1,276	1,826	1,739	74	692	1,345	2,594	2,717	560	289	-69	-768	-978
	2040-2050	1,008	1,153	989	28	-831	168	704	1,770	1,214	987	840	450	-780	-1,186	-1,818
	2050-2060	1,073	610	-255	-1,540	-1,630	-5	330	671	366	312	1,078	280	-926	-1,907	-1,941
	2060+	1,280	-240	-1,700	-1,726	-1,691	0	0	0	0	0	1,280	-240	-1,700	-1,726	-1,691

Table 6.A2: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs expressed as percentages of provincial GDP (nominal), by province, time period and scenario

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Alberta	2016-2030	0.23%	0.57%	0.25%	0.41%	0.54%	0.23%	0.57%	0.25%	0.41%	0.54%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.31%	0.52%	0.38%	0.37%	0.55%	0.03%	0.52%	0.99%	1.38%	1.67%	0.28%	0.00%	-0.61%	-1.02%	-1.11%
	2040-2050	0.36%	0.35%	-0.02%	-0.32%	-1.16%	-0.01%	0.35%	0.94%	0.93%	0.63%	0.37%	0.00%	-0.96%	-1.25%	-1.79%
	2050-2060	0.33%	0.17%	-0.74%	-1.54%	-1.60%	-0.03%	0.07%	0.39%	0.11%	0.08%	0.37%	0.10%	-1.13%	-1.65%	-1.68%
	2060+	0.25%	-0.07%	-1.44%	-1.47%	-1.39%	0.00%	0.00%	0.00%	0.00%	0.00%	0.25%	-0.07%	-1.44%	-1.47%	-1.39%
British Columbia	2016-2030	0.33%	0.33%	0.33%	0.43%	0.55%	0.33%	0.33%	0.33%	0.43%	0.55%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.38%	0.19%	0.57%	0.53%	0.83%	0.07%	0.07%	0.46%	0.56%	0.90%	0.31%	0.12%	0.12%	-0.02%	-0.06%
	2040-2050	0.39%	0.21%	0.60%	0.69%	0.45%	0.04%	0.12%	0.74%	0.98%	0.88%	0.35%	0.09%	-0.13%	-0.29%	-0.43%
	2050-2060	0.34%	0.24%	0.33%	-0.07%	-0.14%	-0.03%	0.04%	0.56%	0.39%	0.18%	0.38%	0.20%	-0.23%	-0.46%	-0.32%
	2060+	0.44%	0.24%	-0.43%	-0.43%	-0.27%	0.00%	0.00%	0.00%	0.00%	0.00%	0.44%	0.24%	-0.43%	-0.43%	-0.27%
Manitoba	2016-2030	0.77%	0.77%	0.77%	0.78%	0.80%	0.77%	0.77%	0.77%	0.78%	0.80%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.74%	1.62%	0.95%	1.16%	1.74%	0.01%	1.17%	0.46%	1.05%	1.69%	0.73%	0.44%	0.49%	0.11%	0.05%
	2040-2050	0.93%	0.87%	1.28%	0.92%	-0.29%	-0.01%	0.72%	1.15%	1.22%	0.72%	0.94%	0.14%	0.13%	-0.30%	-1.01%
	2050-2060	1.46%	0.36%	0.78%	-0.63%	-0.68%	0.10%	0.43%	0.81%	0.43%	0.34%	1.36%	-0.07%	-0.03%	-1.06%	-1.02%
	2060+	1.72%	-0.05%	-0.87%	-0.92%	-0.87%	0.00%	0.00%	0.00%	0.00%	0.00%	1.72%	-0.05%	-0.87%	-0.92%	-0.87%
New Brunswick	2016-2030	0.17%	0.64%	0.47%	0.74%	1.07%	0.17%	0.64%	0.47%	0.74%	1.07%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	-0.87%	-0.88%	0.19%	0.24%	-0.29%	0.10%	0.68%	1.16%	1.41%	1.51%	-0.96%	-1.56%	-0.96%	-1.16%	-1.80%
	2040-2050	-1.23%	-1.35%	-0.92%	-1.63%	-1.95%	-0.49%	0.27%	0.54%	0.52%	0.64%	-0.73%	-1.62%	-1.46%	-2.15%	-2.59%
	2050-2060	-0.02%	-1.19%	-1.19%	-1.88%	-2.00%	0.39%	0.37%	0.66%	0.39%	0.26%	-0.41%	-1.56%	-1.84%	-2.27%	-2.26%
	2060+	-0.42%	-1.54%	-2.05%	-1.97%	-1.97%	0.00%	0.00%	0.00%	0.00%	0.00%	-0.42%	-1.54%	-2.05%	-1.97%	-1.97%
Newfoundland-and-Labrador	2016-2030	0.93%	1.14%	1.18%	2.61%	2.62%	0.93%	1.14%	1.18%	2.61%	2.62%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	-0.51%	-0.67%	1.21%	0.89%	0.77%	0.87%	1.02%	2.91%	2.86%	2.86%	-1.38%	-1.70%	-1.70%	-1.97%	-2.09%
	2040-2050	-0.50%	-0.81%	-1.10%	-2.10%	-2.27%	0.96%	0.98%	0.92%	0.01%	-0.01%	-1.46%	-1.80%	-2.02%	-2.11%	-2.26%
	2050-2060	-0.33%	-0.66%	-1.74%	-2.07%	-1.83%	0.91%	0.83%	0.00%	0.00%	0.00%	-1.24%	-1.50%	-1.75%	-2.08%	-1.83%
	2060+	-1.18%	-1.34%	-1.62%	-1.56%	-1.60%	0.00%	0.00%	0.00%	0.00%	0.00%	-1.18%	-1.34%	-1.62%	-1.56%	-1.60%

Table 6.A2: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs expressed as percentages of provincial GDP (nominal), by province, time period and scenario (Continued)

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Nova Scotia	2016-2030	0.15%	0.22%	0.08%	0.21%	0.56%	0.15%	0.22%	0.08%	0.21%	0.56%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.74%	0.64%	0.95%	0.64%	0.54%	0.06%	-0.05%	0.72%	0.70%	0.61%	0.68%	0.69%	0.23%	-0.06%	-0.07%
	2040-2050	0.55%	0.43%	-0.19%	-0.38%	-0.66%	0.01%	0.00%	0.38%	0.60%	0.73%	0.55%	0.43%	-0.57%	-0.98%	-1.38%
	2050-2060	0.37%	0.22%	-0.23%	-1.47%	-1.29%	-0.03%	-0.05%	0.62%	-0.11%	-0.03%	0.40%	0.28%	-0.85%	-1.36%	-1.26%
	2060+	0.40%	0.27%	-1.17%	-1.21%	-1.12%	0.00%	0.00%	0.00%	0.00%	0.00%	0.40%	0.27%	-1.17%	-1.21%	-1.12%
Ontario	2016-2030	-0.06%	0.25%	0.16%	0.36%	0.43%	-0.06%	0.25%	0.16%	0.36%	0.43%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.47%	0.61%	0.75%	0.68%	0.80%	0.08%	0.42%	0.57%	0.71%	0.87%	0.40%	0.18%	0.18%	-0.03%	-0.07%
	2040-2050	0.60%	0.64%	0.67%	0.40%	-0.07%	0.13%	0.50%	0.73%	0.82%	0.62%	0.47%	0.14%	-0.06%	-0.43%	-0.69%
	2050-2060	0.36%	0.12%	0.03%	-0.53%	-0.55%	-0.23%	0.20%	0.37%	0.15%	0.14%	0.59%	-0.08%	-0.34%	-0.68%	-0.69%
	2060+	0.78%	-0.14%	-0.57%	-0.61%	-0.60%	0.00%	0.00%	0.00%	0.00%	0.00%	0.78%	-0.14%	-0.57%	-0.61%	-0.60%
Prince-Edward-Island	2016-2030	0.36%	0.54%	0.43%	0.64%	0.71%	0.36%	0.54%	0.43%	0.64%	0.71%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.15%	0.28%	0.52%	0.17%	-0.05%	-0.03%	0.52%	0.66%	0.84%	0.70%	0.18%	-0.24%	-0.14%	-0.67%	-0.75%
	2040-2050	-0.24%	-0.92%	-0.42%	-1.03%	-1.55%	-0.29%	-0.04%	0.45%	0.28%	0.32%	0.05%	-0.88%	-0.87%	-1.30%	-1.87%
	2050-2060	0.21%	-1.08%	-0.85%	-1.41%	-1.38%	0.07%	-0.15%	0.20%	0.17%	0.17%	0.14%	-0.93%	-1.05%	-1.57%	-1.55%
	2060+	0.27%	-0.88%	-1.37%	-1.42%	-1.32%	0.00%	0.00%	0.00%	0.00%	0.00%	0.27%	-0.88%	-1.37%	-1.42%	-1.32%
Quebec	2016-2030	0.12%	0.50%	0.13%	0.13%	0.15%	0.12%	0.50%	0.13%	0.13%	0.15%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.07%	0.12%	0.24%	0.38%	0.66%	0.11%	0.36%	0.42%	0.73%	1.03%	-0.05%	-0.24%	-0.18%	-0.35%	-0.38%
	2040-2050	0.13%	-0.17%	-0.04%	-0.30%	-0.58%	0.15%	0.06%	0.33%	0.35%	0.36%	-0.02%	-0.23%	-0.37%	-0.65%	-0.94%
	2050-2060	0.05%	-0.09%	-0.05%	-0.50%	-0.55%	0.01%	0.11%	0.41%	0.26%	0.18%	0.03%	-0.21%	-0.45%	-0.76%	-0.74%
	2060+	0.10%	-0.24%	-0.63%	-0.67%	-0.61%	0.00%	0.00%	0.00%	0.00%	0.00%	0.10%	-0.24%	-0.63%	-0.67%	-0.61%
Saskatchewan	2016-2030	-0.01%	0.53%	0.19%	0.28%	0.70%	-0.01%	0.53%	0.19%	0.28%	0.70%	0.00%	0.00%	0.00%	0.00%	0.00%
	2030-2040	0.76%	1.18%	1.54%	2.20%	2.10%	0.09%	0.83%	1.62%	3.13%	3.28%	0.67%	0.35%	-0.08%	-0.93%	-1.18%
	2040-2050	1.22%	1.39%	1.19%	0.03%	-1.00%	0.20%	0.85%	2.13%	1.46%	1.19%	1.01%	0.54%	-0.94%	-1.43%	-2.19%
	2050-2060	1.29%	0.74%	-0.31%	-1.86%	-1.97%	-0.01%	0.40%	0.81%	0.44%	0.38%	1.30%	0.34%	-1.12%	-2.30%	-2.34%
	2060+	1.54%	-0.29%	-2.05%	-2.08%	-2.04%	0.00%	0.00%	0.00%	0.00%	0.00%	1.54%	-0.29%	-2.05%	-2.08%	-2.04%

Table 6.A3: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs, by province, time period and scenario (CAD millions), no discount rate

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Alberta	2016-2030	940	2,295	1,024	1,665	2,173	940	2,295	1,024	1,665	2,173	-	-	-	-	-
	2030-2040	1,912	3,255	2,370	2,292	3,473	161	3,256	6,182	8,650	10,448	1,751	-1	-3,813	-6,358	-6,976
	2040-2050	3,003	2,955	-144	-2,683	-9,773	-77	2,960	7,890	7,857	5,266	3,080	-5	-8,035	-10,541	-15,039
	2050-2060	3,774	1,906	-8,322	-17,410	-18,122	-386	776	4,455	1,232	859	4,160	1,129	-12,777	-18,642	-18,980
	2060+	3,285	-949	-18,663	-19,001	-18,009	-	-	-	-	-	3,285	-949	-18,663	-19,001	-18,009
British Columbia	2016-2030	1,145	1,166	1,169	1,525	1,928	1,145	1,166	1,169	1,525	1,928	-	-	-	-	-
	2030-2040	2,071	1,030	3,147	2,920	4,566	378	381	2,503	3,057	4,908	1,692	649	643	-137	-341
	2040-2050	2,907	1,543	4,455	5,117	3,333	325	910	5,439	7,224	6,512	2,582	633	-985	-2,107	-3,179
	2050-2060	3,409	2,339	3,262	-650	-1,423	-310	385	5,575	3,887	1,776	3,719	1,954	-2,313	-4,537	-3,199
	2060+	4,936	2,717	-4,868	-4,882	-3,025	-	-	-	-	-	4,936	2,717	-4,868	-4,882	-3,025
Manitoba	2016-2030	650	651	650	653	670	650	651	650	653	670	-	-	-	-	-
	2030-2040	970	2,116	1,246	1,519	2,277	15	1,538	605	1,370	2,217	955	579	641	149	60
	2040-2050	1,642	1,530	2,250	1,624	-508	-17	1,275	2,016	2,149	1,273	1,659	254	234	-525	-1,781
	2050-2060	3,455	850	1,849	-1,488	-1,600	246	1,009	1,909	1,014	804	3,209	-159	-59	-2,502	-2,404
	2060+	4,668	-140	-2,362	-2,492	-2,349	-	-	-	-	-	4,668	-140	-2,362	-2,492	-2,349
New Brunswick	2016-2030	72	279	207	322	467	72	279	207	322	467	-	-	-	-	-
	2030-2040	-588	-596	132	166	-198	66	463	784	954	1,022	-654	-1,059	-652	-788	-1,219
	2040-2050	-1,116	-1,226	-841	-1,486	-1,780	-449	250	489	470	580	-667	-1,475	-1,329	-1,956	-2,359
	2050-2060	-29	-1,457	-1,454	-2,299	-2,453	472	448	803	481	320	-501	-1,904	-2,257	-2,780	-2,773
	2060+	-587	-2,169	-2,875	-2,766	-2,771	-	-	-	-	-	-587	-2,169	-2,875	-2,766	-2,771
Newfoundland-and-Labrador	2016-2030	373	459	476	1,049	1,055	373	459	476	1,049	1,055	-	-	-	-	-
	2030-2040	-321	-423	759	558	484	546	640	1,825	1,791	1,795	-867	-1,063	-1,066	-1,233	-1,311
	2040-2050	-421	-686	-923	-1,768	-1,914	811	826	775	7	-7	-1,233	-1,512	-1,698	-1,775	-1,908
	2050-2060	-375	-748	-1,975	-2,349	-2,075	1,033	945	4	1	0	-1,408	-1,693	-1,979	-2,349	-2,075
	2060+	-1,529	-1,733	-2,101	-2,027	-2,073	-	-	-	-	-	-1,529	-1,733	-2,101	-2,027	-2,073

Table 6.A3: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs, by province, time period and scenario (CAD millions), no discount rate (Continued)

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Nova Scotia	2016-2030	80	118	42	109	296	80	118	42	109	296	-	-	-	-	-
	2030-2040	612	527	785	528	447	52	-41	591	576	507	560	568	194	-49	-60
	2040-2050	616	473	-212	-421	-729	6	0	421	666	807	610	473	-633	-1,087	-1,535
	2050-2060	550	335	-344	-2,187	-1,924	-50	-77	920	-161	-38	600	412	-1,264	-2,025	-1,886
	2060+	679	468	-1,998	-2,071	-1,922	-	-	-	-	-	679	468	-1,998	-2,071	-1,922
Ontario	2016-2030	-599	2,564	1,658	3,632	4,363	-599	2,564	1,658	3,632	4,363	-	-	-	-	-
	2030-2040	7,480	9,588	11,842	10,753	12,613	1,196	6,684	9,009	11,277	13,731	6,284	2,905	2,833	-524	-1,119
	2040-2050	12,651	13,675	14,243	8,426	-1,453	2,664	10,732	15,518	17,502	13,241	9,987	2,943	-1,275	-9,076	-14,693
	2050-2060	10,161	3,381	946	-15,149	-15,596	-6,584	5,775	10,589	4,173	4,046	16,745	-2,393	-9,643	-19,322	-19,641
	2060+	25,473	-4,526	-18,777	-20,119	-19,581	-	-	-	-	-	25,473	-4,526	-18,777	-20,119	-19,581
Prince-Edward-Island	2016-2030	31	46	37	55	61	31	46	37	55	61	-	-	-	-	-
	2030-2040	20	37	69	22	-7	-4	69	88	112	93	24	-32	-19	-89	-100
	2040-2050	-43	-164	-75	-184	-278	-51	-7	81	49	57	9	-157	-156	-234	-335
	2050-2060	51	-260	-205	-339	-332	17	-35	47	40	41	34	-225	-252	-379	-373
	2060+	75	-242	-378	-392	-364	-	-	-	-	-	75	-242	-378	-392	-364
Quebec	2016-2030	653	2,637	679	679	765	653	2,637	679	679	765	-	-	-	-	-
	2030-2040	548	980	1,974	3,069	5,360	924	2,947	3,442	5,951	8,446	-377	-1,967	-1,468	-2,881	-3,087
	2040-2050	1,401	-1,854	-477	-3,274	-6,323	1,650	711	3,615	3,880	3,937	-249	-2,565	-4,092	-7,154	-10,260
	2050-2060	674	-1,387	-667	-7,387	-8,142	188	1,665	5,998	3,882	2,726	486	-3,051	-6,665	-11,268	-10,868
	2060+	1,758	-4,050	-10,583	-11,248	-10,259	-	-	-	-	-	1,758	-4,050	-10,583	-11,248	-10,259
Saskatchewan	2016-2030	-6	504	182	263	662	-6	504	182	263	662	-	-	-	-	-
	2030-2040	1,124	1,740	2,263	3,238	3,084	132	1,227	2,385	4,599	4,818	992	513	-122	-1,362	-1,734
	2040-2050	2,401	2,748	2,358	67	-1,980	400	1,677	4,218	2,894	2,352	2,001	1,071	-1,860	-2,827	-4,332
	2050-2060	3,437	1,953	-817	-4,933	-5,219	-17	1,057	2,148	1,174	998	3,454	896	-2,965	-6,107	-6,217
	2060+	4,698	-880	-6,240	-6,338	-6,208	-	-	-	-	-	4,698	-880	-6,240	-6,338	-6,208

Table 6.A4: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs expressed as percentages of provincial GDP (nominal), by province, time period and scenario, no discount rate

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Alberta	2016-2030	0.27%	0.65%	0.29%	0.47%	0.62%	0.27%	0.65%	0.29%	0.47%	0.62%	-	-	-	-	-
	2030-2040	0.54%	0.92%	0.67%	0.65%	0.98%	0.05%	0.92%	1.75%	2.45%	2.96%	0.50%	0.00%	-1.08%	-1.80%	-1.98%
	2040-2050	0.85%	0.84%	-0.04%	-0.76%	-2.77%	-0.02%	0.84%	2.24%	2.23%	1.49%	0.87%	0.00%	-2.28%	-2.99%	-4.26%
	2050-2060	1.07%	0.54%	-2.36%	-4.93%	-5.14%	-0.11%	0.22%	1.26%	0.35%	0.24%	1.18%	0.32%	-3.62%	-5.28%	-5.38%
	2060+	0.93%	-0.27%	-5.29%	-5.38%	-5.10%	-	-	-	-	-	0.93%	-0.27%	-5.29%	-5.38%	-5.10%
British Columbia	2016-2030	0.37%	0.38%	0.38%	0.49%	0.62%	0.37%	0.38%	0.38%	0.49%	0.62%	-	-	-	-	-
	2030-2040	0.67%	0.33%	1.02%	0.94%	1.48%	0.12%	0.12%	0.81%	0.99%	1.59%	0.55%	0.21%	0.21%	-0.04%	-0.11%
	2040-2050	0.94%	0.50%	1.44%	1.66%	1.08%	0.11%	0.29%	1.76%	2.34%	2.11%	0.84%	0.20%	-0.32%	-0.68%	-1.03%
	2050-2060	1.10%	0.76%	1.06%	-0.21%	-0.46%	-0.10%	0.12%	1.80%	1.26%	0.57%	1.20%	0.63%	-0.75%	-1.47%	-1.03%
	2060+	1.60%	0.88%	-1.58%	-1.58%	-0.98%	-	-	-	-	-	1.60%	0.88%	-1.58%	-1.58%	-0.98%
Manitoba	2016-2030	0.88%	0.88%	0.88%	0.89%	0.91%	0.88%	0.88%	0.88%	0.89%	0.91%	-	-	-	-	-
	2030-2040	1.31%	2.87%	1.69%	2.06%	3.08%	0.02%	2.08%	0.82%	1.86%	3.00%	1.29%	0.78%	0.87%	0.20%	0.08%
	2040-2050	2.22%	2.07%	3.05%	2.20%	-0.69%	-0.02%	1.73%	2.73%	2.91%	1.72%	2.25%	0.34%	0.32%	-0.71%	-2.41%
	2050-2060	4.68%	1.15%	2.51%	-2.02%	-2.17%	0.33%	1.37%	2.59%	1.37%	1.09%	4.35%	-0.22%	-0.08%	-3.39%	-3.26%
	2060+	6.32%	-0.19%	-3.20%	-3.38%	-3.18%	-	-	-	-	-	6.32%	-0.19%	-3.20%	-3.38%	-3.18%
New Brunswick	2016-2030	0.19%	0.73%	0.54%	0.84%	1.22%	0.19%	0.73%	0.54%	0.84%	1.22%	-	-	-	-	-
	2030-2040	-1.54%	-1.56%	0.34%	0.43%	-0.52%	0.17%	1.21%	2.05%	2.49%	2.67%	-1.71%	-2.77%	-1.71%	-2.06%	-3.19%
	2040-2050	-2.92%	-3.21%	-2.20%	-3.89%	-4.65%	-1.18%	0.65%	1.28%	1.23%	1.52%	-1.74%	-3.86%	-3.48%	-5.12%	-6.17%
	2050-2060	-0.07%	-3.81%	-3.80%	-6.01%	-6.42%	1.23%	1.17%	2.10%	1.26%	0.84%	-1.31%	-4.98%	-5.90%	-7.27%	-7.25%
	2060+	-1.54%	-5.67%	-7.52%	-7.23%	-7.25%	-	-	-	-	-	-1.54%	-5.67%	-7.52%	-7.23%	-7.25%
Newfoundland-and-Labrador	2016-2030	1.06%	1.30%	1.35%	2.97%	2.99%	1.06%	1.30%	1.35%	2.97%	2.99%	-	-	-	-	-
	2030-2040	-0.91%	-1.20%	2.15%	1.58%	1.37%	1.54%	1.81%	5.16%	5.07%	5.08%	-2.45%	-3.01%	-3.02%	-3.49%	-3.71%
	2040-2050	-1.19%	-1.94%	-2.61%	-5.00%	-5.42%	2.29%	2.34%	2.19%	0.02%	-0.02%	-3.49%	-4.28%	-4.80%	-5.02%	-5.40%
	2050-2060	-1.06%	-2.12%	-5.59%	-6.64%	-5.87%	2.92%	2.67%	0.01%	0.00%	0.00%	-3.98%	-4.79%	-5.60%	-6.65%	-5.87%
	2060+	-4.33%	-4.90%	-5.94%	-5.73%	-5.86%	-	-	-	-	-	-4.33%	-4.90%	-5.94%	-5.73%	-5.86%

Table 6.A4: Total Net Annual Cost, Infrastructure Expenditures and Fuel Costs expressed as percentages of provincial GDP (nominal), by province, time period and scenario, no discount rate (Continued)

		Total Net Annual Cost (C_{sp})					Infrastructure Expenditures (I_{sp})					Fuel Costs (F_{sp})				
Province	p	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45	REF	CP30	NZ60	NZ50	NZ45
Nova Scotia	2016-2030	0.17%	0.25%	0.09%	0.23%	0.64%	0.17%	0.25%	0.09%	0.23%	0.64%	-	-	-	-	-
	2030-2040	1.31%	1.13%	1.68%	1.13%	0.96%	0.11%	-0.09%	1.27%	1.24%	1.09%	1.20%	1.22%	0.42%	-0.10%	-0.13%
	2040-2050	1.32%	1.02%	-0.45%	-0.90%	-1.56%	0.01%	0.00%	0.90%	1.43%	1.73%	1.31%	1.02%	-1.36%	-2.33%	-3.30%
	2050-2060	1.18%	0.72%	-0.74%	-4.69%	-4.13%	-0.11%	-0.17%	1.98%	-0.35%	-0.08%	1.29%	0.88%	-2.71%	-4.35%	-4.05%
	2060+	1.46%	1.01%	-4.29%	-4.44%	-4.13%	-	-	-	-	-	1.46%	1.01%	-4.29%	-4.44%	-4.13%
Ontario	2016-2030	-0.07%	0.29%	0.19%	0.41%	0.49%	-0.07%	0.29%	0.19%	0.41%	0.49%	-	-	-	-	-
	2030-2040	0.84%	1.08%	1.33%	1.21%	1.41%	0.13%	0.75%	1.01%	1.26%	1.54%	0.70%	0.33%	0.32%	-0.06%	-0.13%
	2040-2050	1.42%	1.53%	1.60%	0.94%	-0.16%	0.30%	1.20%	1.74%	1.96%	1.48%	1.12%	0.33%	-0.14%	-1.02%	-1.65%
	2050-2060	1.14%	0.38%	0.11%	-1.70%	-1.75%	-0.74%	0.65%	1.19%	0.47%	0.45%	1.88%	-0.27%	-1.08%	-2.17%	-2.20%
	2060+	2.86%	-0.51%	-2.11%	-2.26%	-2.20%	-	-	-	-	-	2.86%	-0.51%	-2.11%	-2.26%	-2.20%
Prince-Edward-Island	2016-2030	0.41%	0.61%	0.49%	0.73%	0.81%	0.41%	0.61%	0.49%	0.73%	0.81%	-	-	-	-	-
	2030-2040	0.26%	0.50%	0.92%	0.30%	-0.09%	-0.06%	0.92%	1.17%	1.49%	1.23%	0.32%	-0.43%	-0.25%	-1.19%	-1.32%
	2040-2050	-0.57%	-2.18%	-1.00%	-2.45%	-3.69%	-0.68%	-0.09%	1.08%	0.66%	0.75%	0.12%	-2.09%	-2.08%	-3.10%	-4.45%
	2050-2060	0.68%	-3.45%	-2.73%	-4.50%	-4.41%	0.23%	-0.47%	0.63%	0.54%	0.55%	0.45%	-2.98%	-3.35%	-5.04%	-4.96%
	2060+	1.00%	-3.22%	-5.03%	-5.21%	-4.84%	-	-	-	-	-	1.00%	-3.22%	-5.03%	-5.21%	-4.84%
Quebec	2016-2030	0.14%	0.57%	0.15%	0.15%	0.17%	0.14%	0.57%	0.15%	0.15%	0.17%	-	-	-	-	-
	2030-2040	0.12%	0.21%	0.43%	0.67%	1.16%	0.20%	0.64%	0.75%	1.29%	1.83%	-0.08%	-0.43%	-0.32%	-0.63%	-0.67%
	2040-2050	0.30%	-0.40%	-0.10%	-0.71%	-1.37%	0.36%	0.15%	0.79%	0.84%	0.86%	-0.05%	-0.56%	-0.89%	-1.55%	-2.23%
	2050-2060	0.15%	-0.30%	-0.14%	-1.60%	-1.77%	0.04%	0.36%	1.30%	0.84%	0.59%	0.11%	-0.66%	-1.45%	-2.45%	-2.36%
	2060+	0.38%	-0.88%	-2.30%	-2.44%	-2.23%	-	-	-	-	-	0.38%	-0.88%	-2.30%	-2.44%	-2.23%
Saskatchewan	2016-2030	-0.01%	0.61%	0.22%	0.32%	0.80%	-0.01%	0.61%	0.22%	0.32%	0.80%	-	-	-	-	-
	2030-2040	1.36%	2.10%	2.73%	3.90%	3.72%	0.16%	1.48%	2.88%	5.55%	5.81%	1.20%	0.62%	-0.15%	-1.64%	-2.09%
	2040-2050	2.90%	3.31%	2.84%	0.08%	-2.39%	0.48%	2.02%	5.09%	3.49%	2.84%	2.41%	1.29%	-2.24%	-3.41%	-5.22%
	2050-2060	4.14%	2.35%	-0.99%	-5.95%	-6.29%	-0.02%	1.27%	2.59%	1.42%	1.20%	4.17%	1.08%	-3.58%	-7.36%	-7.50%
	2060+	5.67%	-1.06%	-7.53%	-7.64%	-7.49%	-	-	-	-	-	5.67%	-1.06%	-7.53%	-7.64%	-7.49%

Table 6.A5: Breakdown of modes of electricity generation for each province

	BC	AB	SK	MB	ON	QC	NB	PEI	NS	NL	**Canada**
Hydro	86.3%	2.7%	15.1%	96.9%	23.4%	93.7%	22.8%	-	10.7%	95.6%	59.2%
Wind	2.6%	5.5%	2.9%	2.6%	7.1%	5.2%	6.8%	98.5%	11.0%	0.4%	5.1%
Solar	-	0.1%	0.1%	0.13%	2.5%	-	-	0.5%	0.2%	-	0.6%
Biomass	7.1%	2.5%	-	0.2%	1.2%	0.8%	4.0%	0.7%	2.5%	0.1%	1.7%
Nuclear	-	-	-	-	58.4%	-	38.2%	-	-	-	15.0%
Fossil fuels	4.0%	88.9%	81.4%	0.1%	7.4%	0.4%	28.4%	0.3%	75.7%	3.9%	18.3%
Natural Gas	3.0%	51.0%	40.0%	-	7.3%	0.1%	5.6%	-	14.2%	0.5%	10.2%
Petroleum	1.0%	1.2%	-	0.1%	0.1%	0.3%	8.9%	0.3%	9.6%	3.4%	1.0%
Coal	-	36.7%	41.4%	-	-	-	13.9%	-	51.9%	-	7.1%

Source: Natural Resources Canada, 2021

Table 6.A6: Provincial Gross Domestic Product

Province	GDP (million CAD, 2019)
Alberta	352,884
British Columbia	309,059
Manitoba	73,814
Newfoundland-and-Labrador	35,349
New Brunswick	38,236
Nova Scotia	46,586
Ontario	891,811
Prince-Edward-Island	7,523
Quebec	460,357
Saskatchewan	82,917

ANNEXE D TABLEAU DES COMMUNAUTÉS DU CHAPITRE 7

Table 7.A1: Results from Model IV; list of settlements with corresponding choice of mode of electricity generation, system rollout year, generation costs, storage costs, fossil fuel costs and total optimized system cost (All cost figures expressed in 000s of CAD)

Province/ Territory	Community name	Main power source	Q (MWh/yr)	g	t	A_{gt}	B_{st}	F_t	C'_{gst}
AB	Jasper	Natural Gas	58,342	Solar	2050	16,283	18,614	17,058	51,955
AB	Fort Chipewyan	Diesel	12,843	Solar	2020	8,435	16,098	-	24,533
AB	Chipewyan Lake	Diesel	804	Solar	2020	531	1,008	-	1,539
AB	Narrows Point	Diesel	223	Wind	2020	81	305	-	385
AB	Peace Point	Diesel	59	Solar	2030	40	31	53	125
BC	Masset	Diesel	26,433	Wind	2020	14,767	36,119	-	50,886
BC	Anahim Lake	Diesel	6,649	Solar	2020	5,040	8,334	-	13,374
BC	Kwadacha	Diesel	2,963	Solar	2030	2,542	1,553	2,675	6,770
BC	Telegraph Creek	Diesel	2,612	Solar	2030	1,700	1,369	2,358	5,427
BC	Tsay Keh Dene	Diesel	2,119	Solar	2030	1,739	1,111	1,913	4,762
BC	Uchucklesaht	Diesel	2,119	Solar	2030	1,683	1,111	1,913	4,706
BC	Liard First Nation	Diesel	2,117	Solar	2030	1,380	1,110	1,912	4,401
BC	Kitkatla	Diesel	1,729	Wind	2030	585	1,253	740	2,578
BC	Kulkayu	Diesel	1,673	Wind	2020	1,064	2,286	-	3,350
BC	Owikeno	Diesel	1,400	Wind	2030	962	1,015	659	2,636
BC	Good Hope Lake	Diesel	1,060	Solar	2030	931	556	957	2,443
BC	Sheemahantt Conservancy	Diesel	991	Wind	2030	308	719	323	1,350
BC	Toad River Area	Diesel	754	Wind	2020	374	1,030	-	1,404
BC	Bob Quinn Lake	Diesel	119	Wind	2020	48	163	-	211
BC	Kwikwasut'inuxw Haxwa'mis	Diesel	52	Wind	2020	17	71	-	89
MB	Barren Lands	Diesel	6,503	Wind	2020	2,199	8,885	-	11,084
MB	Shamattawa	Diesel	6,330	Wind	2020	2,773	8,650	-	11,422
MB	Lac Brochet	Diesel	3,557	Wind	2020	1,294	4,860	-	6,154
MB	Brochet	Diesel	3,109	Wind	2020	1,051	4,248	-	5,300
MB	Tadoule Lake	Diesel	2,406	Wind	2020	932	3,288	-	4,220
NL	Natuashish 2	Diesel	9,420	Wind	2020	2,634	12,872	-	15,506
NL	Nain	Diesel	9,377	Wind	2020	2,515	12,813	-	15,328
NL	Charlottetown	Diesel	5,631	Wind	2020	1,458	7,694	-	9,153
NL	Hopedale	Diesel	5,203	Wind	2020	1,302	7,110	-	8,412
NL	Mary's Harbour	Diesel	4,561	Wind	2020	1,284	6,232	-	7,517

Table 7.A1: Results from Model IV; list of settlements with corresponding choice of mode of electricity generation, system rollout year, generation costs, storage costs, fossil fuel costs and total optimized system cost (All cost figures expressed in 000s of CAD) (continued)

Province/ Territory	Community name	Main power source	Q (MWh/yr)	g	t	A_{gt}	B_{st}	F_t	C'_{gst}
NL	Makkovik	Diesel	4,520	Wind	2020	931	6,176	-	7,107
NL	Cartwright	Diesel	4,477	Wind	2020	1,134	6,118	-	7,252
NL	Ramea	Diesel	3,853	Wind	2020	1,157	5,265	-	6,422
NL	Port Hope Simpson	Diesel	3,504	Wind	2020	953	4,788	-	5,741
NL	Rigolet	Diesel	3,049	Wind	2020	740	4,166	-	4,906
NL	Postville	Diesel	2,032	Wind	2020	581	2,777	-	3,358
NL	St Lewis	Diesel	1,604	Wind	2020	435	2,192	-	2,627
NL	Black Tickle	Diesel	1,163	Wind	2020	278	1,589	-	1,867
NL	St. Brendan's	Diesel	1,051	Wind	2030	259	762	657	1,678
NL	François	Diesel	660	Wind	2020	225	902	-	1,126
NL	Grey River	Diesel	583	Wind	2020	187	797	-	983
NL	Little Bay Islands	Diesel	551	Wind	2020	144	753	-	897
NL	McCallum	Diesel	501	Wind	2020	168	685	-	853
NL	Norman's Bay	Diesel	211	Wind	2020	58	288	-	347
NL	Paradise River	Diesel	210	Wind	2020	64	287	-	351
NT	Fort Simpson	Diesel	7,529	Solar	2030	4,148	3,946	4,905	12,999
NT	Inuvik	Natural Gas	11,536	Solar	2050	3,946	3,681	3,373	11,000
NT	Norman Wells	Natural Gas	9,110	Solar	2050	2,897	2,907	2,664	8,467
NT	Tuktoyaktuk	Diesel	4,229	Wind	2020	1,977	5,779	-	7,756
NT	Fort McPherson	Diesel	3,459	Solar	2020	2,831	4,336	-	7,166
NT	Aklavik	Diesel	3,192	Wind	2020	1,602	4,362	-	5,964
NT	Fort Providence	Diesel	3,123	Solar	2020	2,074	3,914	-	5,988
NT	Délı̨ne	Diesel	2,756	Wind	2020	1,240	3,766	-	5,006
NT	Fort Good Hope	Diesel	2,749	Wind	2020	1,487	3,756	-	5,244
NT	Tulita	Diesel	2,433	Wind	2020	1,221	3,325	-	4,545
NT	Fort Liard	Diesel	2,279	Solar	2030	1,321	1,195	1,951	4,467
NT	Ulukhaktok	Diesel	2,069	Wind	2020	622	2,827	-	3,449
NT	Whatı̨	Diesel	1,769	Wind	2020	675	2,417	-	3,092
NT	Łutselk'e	Diesel	1,648	Wind	2020	725	2,252	-	2,977
NT	Paulatuk	Diesel	1,461	Wind	2020	757	1,996	-	2,754

Table 7.A1: Results from Model IV; list of settlements with corresponding choice of mode of electricity generation, system rollout year, generation costs, storage costs, fossil fuel costs and total optimized system cost (All cost figures expressed in 000s of CAD) (continued)

Province/ Territory	Community name	Main power source	Q (MWh/yr)	g	t	A_{gt}	B_{st}	F_t	C'_{gst}
NT	Gamètì	Diesel	1,130	Wind	2020	492	1,544	-	2,036
NT	Sachs Harbour	Diesel	954	Wind	2020	447	1,304	-	1,751
NT	Tsiigehtchic	Diesel	777	Wind	2020	497	1,062	-	1,559
NT	Wrigley	Diesel	737	Solar	2030	423	386	542	1,351
NT	Wekweètì	Diesel	662	Wind	2020	257	905	-	1,162
NT	Colville Lake	Diesel	627	Wind	2020	287	857	-	1,144
NT	Sambaa K'e	Diesel	451	Wind	2020	221	617	-	837
NT	Nahanni Butte	Diesel	399	Solar	2030	230	209	293	733
NT	Jean Marie River	Diesel	331	Solar	2030	179	173	216	568
NT	Kakisa	Diesel	326	Wind	2020	188	445	-	633
NU	Iqaluit	Diesel	59,140	Wind	2020	25,799	80,811	-	106,610
NU	Rankin Inlet	Diesel	18,113	Wind	2020	5,223	24,750	-	29,974
NU	Cambridge Bay	Diesel	12,359	Wind	2020	4,797	16,888	-	21,685
NU	Baker Lake	Diesel	8,917	Wind	2020	3,120	12,185	-	15,305
NU	Arviat	Diesel	8,661	Wind	2020	2,459	11,835	-	14,294
NU	Igloolik	Diesel	6,587	Wind	2020	2,593	9,001	-	11,594
NU	Pangnirtung	Diesel	6,506	Wind	2020	2,726	8,890	-	11,616
NU	Pond Inlet	Diesel	6,355	Wind	2020	3,722	8,684	-	12,406
NU	Kugluktuk	Diesel	5,839	Wind	2020	3,302	7,979	-	11,281
NU	Cape Dorset	Diesel	5,685	Wind	2020	1,901	7,768	-	9,670
NU	Gjoa Haven	Diesel	5,619	Wind	2020	2,295	7,678	-	9,973
NU	Resolute	Diesel	4,607	Wind	2020	1,986	6,295	-	8,281
NU	Naujaat	Diesel	4,115	Wind	2020	1,560	5,623	-	7,183
NU	Taloyoak	Diesel	3,964	Wind	2020	1,877	5,417	-	7,293
NU	Clyde River	Diesel	3,931	Wind	2020	1,385	5,371	-	6,756
NU	Sanikiluaq	Diesel	3,718	Wind	2020	1,001	5,080	-	6,082
NU	Coral Harbour	Diesel	3,525	Wind	2020	1,459	4,817	-	6,276
NU	Hall Beach	Diesel	3,376	Wind	2020	1,371	4,613	-	5,984
NU	Arctic Bay	Diesel	3,194	Wind	2020	1,599	4,364	-	5,964
NU	Kugaaruk	Diesel	2,829	Wind	2020	1,040	3,866	-	4,906

Table 7.A1: Results from Model IV; list of settlements with corresponding choice of mode of electricity generation, system rollout year, generation costs, storage costs, fossil fuel costs and total optimized system cost (All cost figures expressed in 000s of CAD) (continued)

Province/ Territory	Community name	Main power source	Q (MWh/yr)	g	t	A_{gt}	B_{st}	F_t	C'_{gst}
NU	Qikiqtarjuaq	Diesel	2,776	Wind	2020	996	3,793	-	4,789
NU	Kimmirut	Diesel	2,079	Wind	2020	873	2,841	-	3,714
NU	Chesterfield Inlet	Diesel	2,070	Wind	2020	566	2,829	-	3,395
NU	Whale Cove	Diesel	1,844	Wind	2020	507	2,520	-	3,026
NU	Grise Fiord	Diesel	1,237	Wind	2020	542	1,690	-	2,232
ON	Sandy Lake	Diesel	12,365	Solar	2020	8,414	15,498	-	23,913
ON	Pikangikum	Diesel	11,719	Solar	2020	7,783	14,689	-	22,472
ON	Fort Hope	Diesel	6,478	Solar	2030	3,569	3,396	4,100	11,065
ON	Kitchenuhmaykoosib	Diesel	6,402	Wind	2020	2,188	8,749	-	10,937
ON	Whitesand	Diesel	5,483	Solar	2030	3,532	2,874	4,377	10,784
ON	Deer Lake	Diesel	5,333	Wind	2020	2,579	7,288	-	9,866
ON	Kasabonika	Diesel	5,150	Wind	2020	2,258	7,038	-	9,295
ON	Wunnumin Lake	Diesel	4,813	Solar	2030	2,661	2,523	3,224	8,408
ON	Armstrong	Diesel	4,794	Solar	2030	2,559	2,513	3,828	8,899
ON	Weagamow Lake	Diesel	4,712	Solar	2020	3,261	5,906	-	9,167
ON	Keewaywin	Diesel	4,317	Solar	2030	2,840	2,263	2,893	7,996
ON	North Spirit Lake	Diesel	4,317	Solar	2030	2,293	2,263	3,094	7,649
ON	Muskrat Dam Lake	Diesel	4,118	Solar	2030	2,242	2,159	2,875	7,276
ON	Poplar Hill	Diesel	4,102	Solar	2030	2,140	2,150	2,443	6,734
ON	Summer Beaver	Diesel	4,035	Solar	2030	2,243	2,115	2,573	6,930
ON	Sachigo Lake	Diesel	3,299	Solar	2020	2,295	4,135	-	6,430
ON	Peawanuck	Diesel	3,204	Wind	2020	1,305	4,378	-	5,682
ON	Webequie	Diesel	3,070	Wind	2020	1,047	4,196	-	5,243
ON	Fort Severn	Diesel	3,066	Wind	2020	1,107	4,189	-	5,296
ON	Bearskin Lake	Diesel	2,880	Wind	2020	1,622	3,936	-	5,558
ON	Kingfisher Lake	Diesel	2,724	Wind	2020	1,591	3,722	-	5,313
ON	Wapekeka Reserve 1	Diesel	2,610	Wind	2020	972	3,567	-	4,539
ON	Neskantaga	Diesel	2,122	Wind	2020	1,036	2,900	-	3,936
ON	Ogoki	Diesel	2,016	Wind	2020	958	2,754	-	3,712
ON	Gull Bay	Diesel	1,189	Wind	2020	716	1,624	-	2,340

Table 7.A1: Results from Model IV; list of settlements with corresponding choice of mode of electricity generation, system rollout year, generation costs, storage costs, fossil fuel costs and total optimized system cost (All cost figures expressed in 000s of CAD) (continued)

Province/ Territory	Community name	Main power source	Q (MWh/yr)	g	t	A_{gt}	B_{st}	F_t	C'_{gst}
ON	Sultan	Diesel	479	Solar	2020	331	601	-	932
ON	Biscotasing	Diesel	436	Solar	2030	292	229	391	912
ON	Wawakapewin	Diesel	270	Wind	2020	126	368	-	494
ON	Oba	Diesel	253	Solar	2020	178	317	-	495
QC	Les Îles-de-la-Madeleine	Heavy fuel oil	181,648	Wind	2020	42,726	248,211	-	290,937
QC	Kuujjuaq	Diesel	20,333	Wind	2020	7,555	27,784	-	35,339
QC	La Romaine	Diesel	14,022	Wind	2020	4,244	19,160	-	23,405
QC	Obedjiwan	Diesel	13,294	Wind	2020	4,656	18,165	-	22,821
QC	Kuujjuarapik	Diesel	12,257	Wind	2020	3,570	16,748	-	20,319
QC	Puvirnituq	Diesel	11,962	Wind	2020	3,519	16,345	-	19,864
QC	Inukjuak	Diesel	10,269	Wind	2020	2,978	14,032	-	17,010
QC	Salluit	Diesel	8,326	Wind	2020	2,579	11,377	-	13,956
QC	Kangiqsujuaq	Diesel	4,815	Wind	2020	1,657	6,579	-	8,237
QC	Kangiqsualujjuaq	Diesel	4,675	Wind	2020	1,408	6,388	-	7,796
QC	L'Île d'Anticosti	Diesel	4,477	Wind	2020	1,547	6,118	-	7,664
QC	Akulivik	Diesel	3,801	Wind	2020	1,124	5,194	-	6,318
QC	Kangirsuk	Diesel	3,601	Wind	2020	1,161	4,921	-	6,082
QC	Lac-Rapide	Diesel	3,539	Wind	2020	2,411	4,836	-	7,247
QC	Umiujaq	Diesel	2,989	Wind	2020	860	4,084	-	4,945
QC	Quaqtaq	Diesel	2,863	Wind	2020	891	3,912	-	4,803
QC	Tasiujaq	Diesel	2,508	Wind	2020	883	3,427	-	4,310
QC	Ivujivik	Diesel	2,373	Wind	2020	714	3,243	-	3,956
QC	Aupaluk	Diesel	1,905	Wind	2020	653	2,603	-	3,256
QC	Clova	Diesel	788	Solar	2030	541	413	660	1,614
YT	Watson Lake	Diesel	14,902	Solar	2030	9,641	7,811	5,132	22,584
YT	Old Crow	Diesel	2,350	Solar	2030	1,478	1,232	1,750	4,460
YT	Destruction Bay	Diesel	1,793	Wind	2030	540	1,300	617	2,458
YT	Beaver Creek	Diesel	1,775	Solar	2020	1,379	2,225	-	3,604