Integrated Environmental-Economic Analysis of Different Scenarios Regarding Forest-based Bioenergy in Quebec

by

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Analyse environnementale-économique intégrée de différents scénarios concernant la bioénergie à base de forêt au Québec

Hamed KOUCHKI PENCHAH

RÉSUMÉ

Cette étude fournit des informations précieuses aux décideurs en examinant la contribution du secteur forestier à la réalisation d'une décarbonisation profonde. Elle développe une approche de modélisation détaillée qui prend en compte différentes voies de bioénergie à base de forêt dans un cadre techno-économique afin de déterminer la contribution de la bioénergie à base de forêt dans la lutte contre le changement climatique. Ces voies sont incorporées dans le modèle énergétique NATEM-Québec, un modèle énergétique détaillé ascendante. Les résultats démontrent l'importance de la bioénergie à base de forêt en tant que composante clé de la stratégie de décarbonisation du Québec et mettent en évidence son potentiel pour d'autres régions connaissant un déclin des produits forestiers traditionnels. De plus, les résultats soulignent les défis de la décarbonisation des secteurs du transport et de l'industrie lourde, tout en insistant sur la nécessité d'une électrification étendue et d'une utilisation accrue de la bioénergie. Cette thèse développe également une approche intégrée en combinant le modèle de modélisation des peuplements et des paysages CBM-CFS3 avec NATEM-Québec afin d'éliminer l'hypothèse de neutralité carbone biogénique prévalente dans la littérature précédente, en abordant les erreurs de comptabilité potentielles et en évitant les décisions biaisées. L'intégration des flux de CO_2 biogénique dans le modèle du système énergétique révèle le rôle de la séquestration forestière dans l'atténuation des émissions et la nécessité d'inclure les émissions biogéniques dans les contributions déterminées au niveau national. La prise en compte des émissions biogéniques conduit à une réduction de l'utilisation de la biomasse et de la bioénergie dans les scénarios d'émissions de gaz à effet de serre. Par conséquent, supposer la neutralité carbone biogénique peut entraîner des décisions biaisées car cela permet au modèle d'utiliser davantage de biomasse sans être contraint par les émissions de CO_2 biogénique. Bien qu'un investissement immédiat dans la bioénergie avec capture et stockage du carbone, la capture directe de l'air et d'autres technologies d'émissions négatives puisse ne pas être réalisable, une transition vers des stratégies de gestion forestière rentables peut faciliter la réalisation d'émissions nettes nulles d'ici 2050. De plus, cette recherche entreprend une analyse techno-économique régionalisée approfondie, en mettant l'accent sur différentes voies de l'hydrogène dans la province de Québec, au Canada, en suivant l'approche intégrée développée. L'étude met en évidence l'importance de l'hydrogène, à la fois bleu et vert, dans la réalisation d'objectifs ambitieux de zéro émission nette, en particulier dans les secteurs industriels difficiles à décarboner. L'adoption généralisée de l'électrolyse est recommandée dans les situations où l'électrification n'est pas réalisable ou lorsque le stockage d'énergie est requis. Dans l'ensemble, cette recherche fournit des informations précieuses et des recommandations aux décideurs politiques et met en évidence l'importance de la bioénergie à base de forêt et de l'hydrogène dans la transition énergétique vers une économie durable à émissions nettes nulles.

Mots-clés: transition énergétique, émissions nettes nulles, bioénergie à base de forêt, technologies d'émissions négatives, BECCS, séquestration en forêt, CO_2 biogénique, hydrogène, modèle TIMES.

Integrated environmental-economic analysis of different scenarios regarding forest-based bioenergy in Quebec

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ABSTRACT

This study provides valuable insights for decision-makers by examining the contribution of the forest sector in achieving deep decarbonization. It develops a detailed modeling approach that considers different forest-based bioenergy pathways within a techno-economic framework to determine the contribution of forest-based bioenergy in mitigating climate change. These pathways are incorporated into the NATEM-Québec, a detailed bottom-up energy model. The results demonstrate the importance of forest-based bioenergy as a key component of Quebec's decarbonization strategy and highlight its potential for other regions experiencing a decline in traditional forest products. Furthermore, the findings emphasize the challenges of decarbonizing the transportation and heavy industry sectors while also emphasizing the need for extensive electrification and increased bioenergy usage. This thesis also develops an integrated approach by integrating CBM-CFS3, a stand- and landscape-level modeling framework, with NATEM-Québec to eliminate the carbon neutrality assumption prevalent in previous literature, addressing potential accounting errors and biased decision-making. Integrating biogenic CO_2 flows into the energy system model reveals the role of forest sequestration in mitigating emissions and the need to include biogenic emissions in nationally determined contributions. Accounting for biogenic emissions leads to reduced biomass and bioenergy usage in GHG scenarios. Therefore, assuming biogenic carbon neutrality may result in biased decision-making because it allows the model to use more biomass without being constrained by biogenic CO_2 emissions. While immediate investment in bioenergy with carbon capture and storage, direct air capture, and other negative emission technologies may not be feasible, transitioning towards cost-effective forest management strategies can facilitate achieving net-zero emissions by 2050. Moreover, this research undertakes an extensive regionalized techno-economic analysis, focusing on various hydrogen pathways within the province of Quebec, Canada, following the developed integrated approach. The study highlights the significance of hydrogen, both blue and green, in achieving ambitious net-zero emission targets, particularly in difficult-to-decarbonize industrial sectors. The wider adoption of electrolysis is recommended for situations where electrification is not feasible, or energy storage is required. Overall, this research provides valuable insights and recommendations for policymakers and highlights the significance of forest-based bioenergy and hydrogen in the energy transition toward a sustainable, net-zero emission economy.

Keywords: energy transition, net-zero emission, forest-based bioenergy, negative emission technologies, BECCS, in-forest sequestration, biogenic CO_2, hydrogen, TIMES model

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AEL	Alkaline electrolysis
AEM	Alkaline anion exchange membrane
AFOLU	Agriculture, Forestry, and Other Land-Use
ATR	Auto thermal reforming
BAU	Business-as-usual
BECCS	Bioenergy with carbon capture and storage
BIGCC	Biomass Integrated Gasification Combined Cycle
BtL	Biomass-to-liquid
CAD	Canadian dollars
CBM-CFS3	Carbon Budget Model of the Canadian Forest Sector
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CDR	Carbon dioxide removal
CHP	Combined heat and power
DAC	Direct air capture
E3	Energy-Environment-Economy
EFGT	Externally Fired Gas Turbine
FT	Fischer-Tropsch
GHG	Greenhouse gas
HCs	Hydrocarbon fuels
HDO	Hydrodeoxygenation
HTC	Hydrothermal carbonization
HTG	Hydrothermal gasification
HTL	Hydrothermal liquefaction
HWPs	Harvested wood products
IEA	International Energy Agency

IPCC	The Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LP	Linear programming
LULUCF	Land Use, Land-use Change and Forestry
NATEM	North American TIMES Energy Model
NDC	Nationally Determined Contribution
NETs	Negative emission technologies
NIR	National Inventory Report
OSB	Oriented strand board
PEM	Polymer electrolyte membrane
PEP	Primary energy production
Pox	Partial oxidation
PtG	Power-to-Gas
REF	Reference
RES	Reference Energy System
SBW	Spruce budworm
SMR	Steam reforming
SNG	Synthesis gas
SOEL	Solid oxide electrolysis
TDO	Thermal deoxygenation
TIMES	The Integrated MARKAL-EFOM System
UNFCCC	United Nations Framework Convention on Climate Change
WGS	Water gas shift

INTRODUCTION

The forest industry has experienced significant changes due to declining demand for traditional forest products in many countries such as the United States (US), Canada, and Nordic countries (Hurmekoski *et al.*, 2018 ; Jåstad *et al.*, 2019). This declining trend has spurred the development of new products and processes. The climate change mitigation potential of forest products provides further incentives (Xu *et al.*, 2018). Forest-based bioenergy has emerged as one such product that has gained attention, primarily due to its lower carbon balance compared to fossil fuels, storability unlike many renewables, and adaptability within the existing fossil infrastructure (Allen *et al.*, 2016).

As a signatory to the Paris Agreement (UNFCCC, 2015), every country is obligated to establish a Nationally Determined Contribution (NDC). For example, Canada (Government of Canada, 2020), the European Union (European Commission, 2018), New Zealand, United Kingdom, established a net-zero emissions target by 2050, Sweden by 2045, Norway by 2030 (Welfle, Thornley et Röder, 2020), and China by 2060 (Vaughan, 2020). Achieving pathways that limit warming to 2°C or lower entails extensive carbon dioxide removal, which involves a significant transformation of the land surface, an expansion of forest cover, and the deployment of negative emission technologies (NETs) (Riahi *et al.*, 2022 ; Lecocq *et al.*, 2022).

NETs that are available include coastal blue carbon, carbon mineralization, direct air capture (DAC), bioenergy with carbon capture and storage (BECCS), and terrestrial carbon removal and sequestration. However, only BECCS and terrestrial carbon removal and sequestration (particularly afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils) are ready for large-scale deployment. These NETs have low to moderate costs (\$100/t CO_2 or less) and have a high potential for safe scale-up from the present implementation (NASEM, 2019). In addition to NETs, green hydrogen is increasingly being considered as a clean energy carrier in different countries' roadmaps for meeting the Paris agreement target (NRCan, 2020; European Commission, 2020 ; FCHEA, 2021).

To support policy makers in defining optimal pathways to achieve their targets, the utilization of tools such as techno-economic models is essential. This work relies on the North American TIMES Energy Model (NATEM) (Vaillancourt *et al.*, 2017), a bottom-up energy system model, to take into account competition between the pathways on the market. Such models are considered relevant instruments to generate different scenarios, preparing deep insights for choosing a cost-effective or advantageous mix of technologies considering various assumptions and policy alternatives. NATEM belongs to the TIMES models family and is a highly detailed multi-regional optimization model of the Canadian energy sectors. It uses various and thorough parameters to optimize defined scenarios based on legislative policies, such as GHG emissions constraints. However, NATEM possesses certain limitations that need to be addressed. The first limitation to be addressed in this research is the lack of inclusion of various forest bioenergy technologies within the model. This absence hinders a comprehensive analysis of the potential benefits and impacts of such technologies on policy outcomes. Another significant drawback of NATEM, as well as TIMES models in general, is the disregard for biogenic carbon. Carbon uptake and release by biomass is known as biogenic carbon (Berndes *et al.*, 2016). Biogenic CO_2 emissions from bioenergy sources, according to IPCC (Eggleston *et al.*, 2006), should not be included in national greenhouse gas inventories since bioenergy CO_2 emissions are included in the Agriculture, Forestry, and Other Land-Use (AFOLU) sector. Accordingly, government initiatives endorse bioenergy as an alternative carbon-neutral energy source for fossil fuels (Liu *et al.*, 2017). The carbon neutrality assumption might be acceptable when the rotation length of biomass is short such as annual crops. The assumption, however, may not remain true when the sequestration period is lengthy, as in the case of forest trees (Cherubini *et al.*, 2011 ; Guest *et al.*, 2013). Bioenergy systems can lead to positive, neutral, or negative effects on biogenic carbon stocks (Berndes *et al.*, 2016). For instance, using roundwood as bioenergy lead to quite long carbon payback periods (Bernier et Paré, 2013), whereas harvested residues from managed forests (Smyth *et al.*, 2017) or damaged forest residues (Lamers *et al.*, 2014) as biomass source have shown a positive climate change mitigation potential. The carbon-neutral assumption is increasingly being

questioned, with several studies indicating that it may result in accounting errors and biased decision-making (Berndes *et al.*, 2016 ; Liu *et al.*, 2017 ; Albers *et al.*, 2019).
Many studies (Head *et al.*, 2019 ; Smyth *et al.*, 2014 ; Smyth *et al.*, 2017 ; Werner *et al.*, 2010 ; Cintas *et al.*, 2017 ; Gustavsson *et al.*, 2017 ; Lamers *et al.*, 2014 ; Moreau *et al.*, 2022 ; Landry *et al.*, 2021) have evaluated the role of forest management or bioenergy in climate change mitigation using modeling frameworks that simulate the dynamics of forest carbon stocks. However, these studies cannot assess the most cost-effective pathways to reduce GHG emissions. Several research efforts (Börjesson *et al.*, 2014 ; Dodder *et al.*, 2015 ; König, 2011 ; Panos et Kannan, 2016 ; Zhao *et al.*, 2015 ; Jåstad *et al.*, 2021 ; Hugues, Assoumou et Maizi, 2016 ; Levasseur *et al.*, 2017 ; Vaillancourt, Bahn et Levasseur, 2019) have employed energy system models to examine the role of bioenergy while taking into account market competition among different pathways, but they usually disregard the dynamics of soil organic carbon and land use (Frank *et al.*, 2015) and follow a carbon neutrality assumption. Similarly, several studies (Blanco *et al.*, 2019 ; Damman *et al.*, 2021 ; Espegren *et al.*, 2021 ; van der Zwaan, Lamboo et Dalla Longa, 2021 ; Yang *et al.*, 2022) have been conducted to assess the role of hydrogen in climate change mitigation while accounting for market competition across various pathways, following a carbon neutrality assumption.

The objective of this thesis is to develop an integrated approach that combines a techno-economic model of the energy system with a forest carbon model. This combined framework provides a more robust and comprehensive assessment of the crucial role played by forest bioenergy, hydrogen, and negative emissions technologies (NETs) within decarbonization pathways while eliminating the carbon neutrality assumption present in previous literature. By leveraging the strengths of both models, this research seeks to enhance our understanding of the potential contributions and impacts of these key elements, enabling policymakers and stakeholders to make more informed decisions in shaping sustainable and effective decarbonization strategies.

The remainder of this dissertation is structured as follows. Chapter 1 describes energy system modeling approaches and summarizes previous works on the role of bioenergy, forest management, and green hydrogen in the energy transition. Then it presents the research questions and objectives of this dissertation. Chapter 2 focuses on factors affecting GHG emissions associated with forest-based bioenergy technologies in the energy system to investigate potential decarbonization pathways by 2050. The study was published in the journal of Energy Conversion and Management. Chapter 3 describes an integrated approach to address the carbon-neutrality assumption when assessing the role of bioenergy in climate change mitigation pathways. The study was published in the journal of Environmental Science & Technology. In Chapter 4, the integrated approach developed in the previous chapters, along with the lessons learned, are applied to measure the role of hydrogen under different policy scenarios. The article was submitted for publication to the International Journal of Hydrogen Energy. Eventually the dissertation is concluded in the Conclusions chapter that also offers recommendation for the future studies.

CHAPTER 1

LITERATURE REVIEW

This chapter provides a concise introduction to energy system modeling approaches, along with essential concepts and vocabulary necessary for comprehending the thesis. It outlines the general context, highlights the overarching issues, and presents the current state-of-the-art in modeling forest-based bioenergies, forest management strategies, hydrogen, and the integration of a specific model with TIMES. The chapter culminates with a clear statement of the research question and the corresponding objectives, setting the foundation for the subsequent chapters.

1.1 Climate change mitigation pathways

A wide range of climate change mitigation options exist to address the pressing challenge of global warming. These options encompass various sectors such as energy, AFOLU, transportation, buildings, and industry. Figure 1.1 shows an overview of the available options in each sector along their approximate costs and potential in 2030 (Skea *et al.*, 2022). Prominent among these options is the deployment of renewable energy sources like solar and wind power, which have the potential to significantly reduce greenhouse gas emissions while becoming cost-competitive with fossil fuels. Additionally, improving energy efficiency in buildings, industries, and transportation systems can yield substantial emissions reductions. Other mitigation strategies include the adoption of sustainable land management practices, such as afforestation and reforestation, which help sequester carbon dioxide from the atmosphere. According to Skea et al. (2022), adopting a holistic approach that incorporates a range of mitigation options across diverse sectors is essential for effectively tackling climate change and minimizing its consequences.

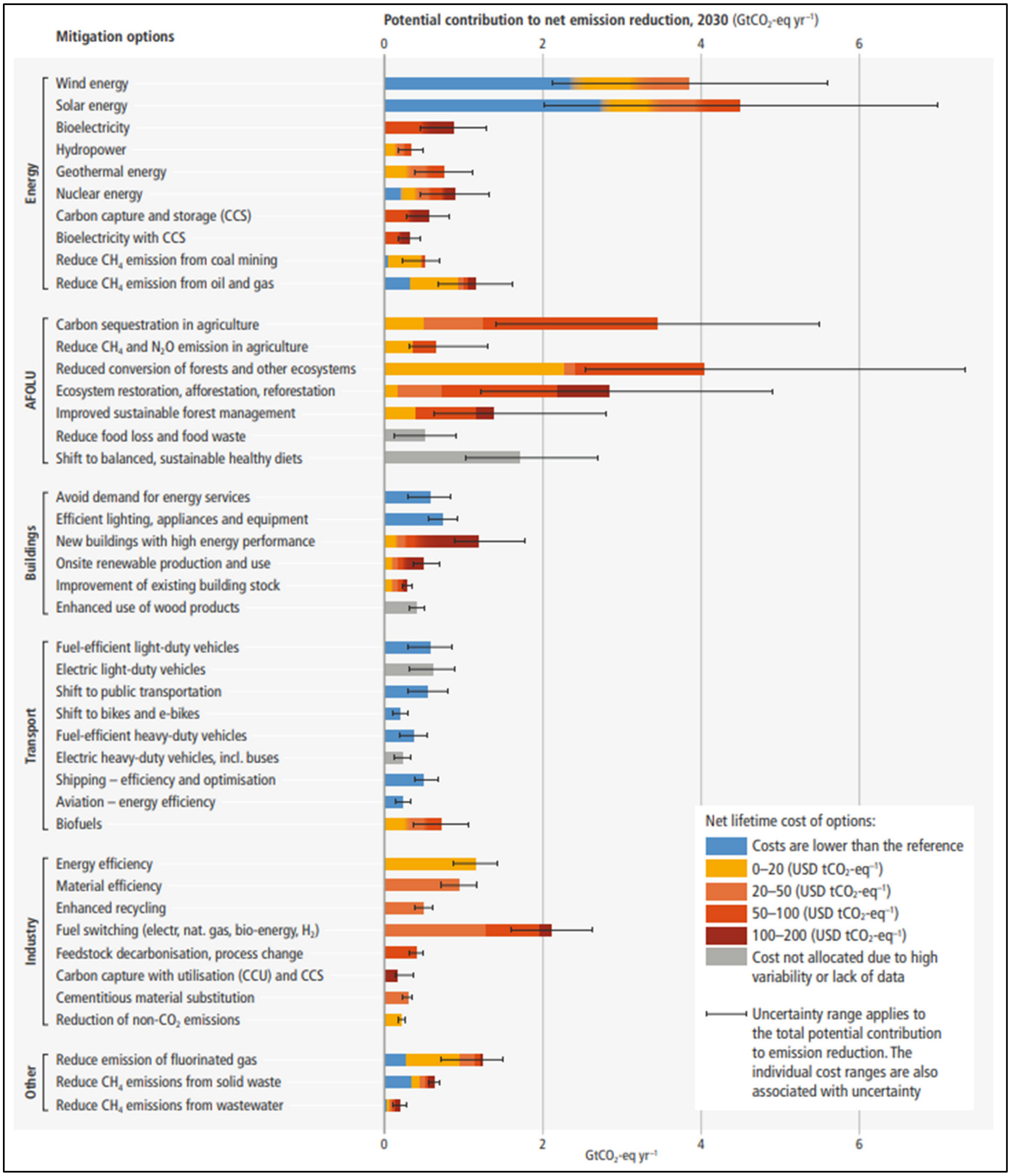

Figure 1.1 Summary of the potential and cost ranges of climate change mitigation options in 2030
Taken from Skea et al. (2022)

1.1.1 Carbon dioxide removal options

Climate change mitigation pathways that limit warming to 2°C or below require deep carbon dioxide removal (CDR) through a large-scale transformation of the land surface, an increase in forest cover, and the deployment of negative emission technologies (NETs) Riahi *et al.*, 2022 ; Lecocq *et al.*, 2022). The inclusion of CDR strategies in national mitigation portfolios, targeting either net zero or net-negative emissions, is crucial. However, the specific methods, as well as the magnitude and timing of their implementation, will vary based on the desired level of gross emissions reductions, the effective management of sustainability and feasibility constraints, and the evolving political and social acceptability (Babiker *et al.*, 2022). Figure 1.2 classifies various methods of CDR or NETs based on implementation options, the earth system, and storage medium. Four NETs are ready for large-scale deployment, namely, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and storage (BECCS). These NETs incur low to moderate costs ($100/t CO_2 or less) and have significant potential for safe scale-up from present implementation. Direct air capture (DAC) is another emerging NET option, although its costs are still prohibitively high (NASEM, 2019).

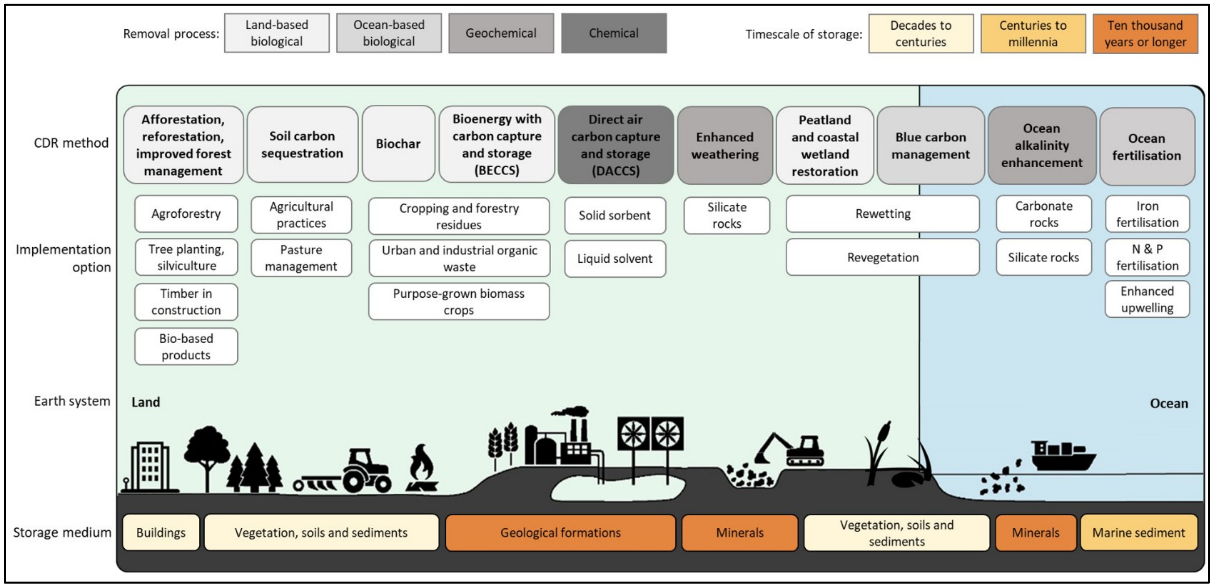

Figure 1.2 Negative emission technologies (NETs)
Taken from Babiker et al. (2022)

Carbon capture and storage (CCS) and carbon capture and utilization (CCU) are not considered NETs since they do not directly remove CO_2 from the atmosphere. However, if the CO_2 is captured from the atmosphere, either through biomass or directly from ambient air, and subsequently stored in geological reservoirs or utilized in durable products, CCS and CCU can be incorporated as part of CDR methods (Babiker *et al.*, 2022).

1.1.2 The role of forests

Carbon dioxide removal can be accomplished through forestry practices such as intensifying afforestation/reforestation, and improving forest management strategies (NASEM, 2019). Global afforestation/reforestation is expected to remove 1–6 Gt CO_2-eq per year. It has been projected that the area required to achieve this target will range between 70 and 500 Mha (Griscom *et al.*, 2017 ; Smith *et al.*, 2016). The global mitigation potential of improved forest management is also estimated to be between 0.1 and 2.1 Gt CO_2-eq per year (Nabuurs *et al.*, 2022). The major limitation of CDR through in forest carbon storage is the demand for wood that limits possible reductions in harvest rate, and the inability to fully implement forest management practices (NASEM, 2019). A forest managed for wood production may store less carbon than a forest that is left unharvested. However, disturbances may reduce the amount of carbon stored in unharvested boreal forests. While CO_2 sequestered by forestry practices can be stored for decades, the associated sinks will gradually become satuated (Riahi *et al.*, 2022 ; Lecocq *et al.*, 2022). Carbon storage through the increased usage and preservation of harvested wood products (HWP) is also an available near-term approach for removing CO_2 (Churkina *et al.*, 2020 ; Pomponi *et al.*, 2020 ; Mishra *et al.*, 2022 ; NASEM, 2019).

1.1.3 Bioenergy with carbon capture and storage

BECCS plays an essential role in most climate change mitigation pathways limiting global temperature to 2°C or below (Hanssen *et al.*, 2020). The estimated range for BECCS CO_2 removal fluxes is between 3.5 and 15 Gt CO_2-eq per year, even though the associated land requirements for the upper limit were expected to be as high as 700 Mha (NASEM, 2019). The deployment of BECCS must incorporate the numerous strategies in which forests and forest-related sectors contribute to CDR because there could be trade-offs between carbon sequestration, storage, and biomass production, as well as between short-term and long-term GHG reduction targets (Berndes *et al.*, 2016). According to Hanssen et al. (2020), the IPCC's projected CO_2 sequestration through BECCS is achievable biophysically, although, given its extensive land requirements, a much more limited and earlier deployment was recommended. Section 1.3 provides a comprehensive description of bioenergy production pathways.

1.1.4 Hydrogen as a clean energy carrier

Global hydrogen production in 2021 reached 94 Mt, primarily through natural gas reforming without CCS or CCU, releasing more than 900 Mt CO_2 into the atmosphere. Less than 1% of this hydrogen was produced using fossil fuels with CCU or electricity and the rest was produced via coal gasification, oil, and as a by-product of naphtha reforming at refineries (IEA, 2022). Hydrogen is increasingly beingconsidered in different countries' roadmaps to meet the Paris agreement's target of limiting warming to 2°C or less, including the United States (FCHEA, 2021), the United Kingdom (Department for Business E& IS, 2021), the European Union (European Commission, 2020), Japan (METI, 2019), Australia (COAG Energy Council, 2019), and Canada (NRCan, 2020).

The hydrogen produced by reforming natural gas is known as grey hydrogen and combining this process with CCS/CCU results in lower process emissions and is called blue hydrogen. Green hydrogen is produced using renewable electricity in electrolyzers. Gasification of biomass could also be considered as another method for producing green hydrogen. Combining biomass gasification with CCS (BECCS) results in negative emissions (if the biomass source is carbon neutral) and is one of the available negative emission technologies (NASEM, 2019 ; Capurso *et al.*, 2022). Blue and green hydrogen have attracted attention, primarily because of the ability to minimize reliance on fossil fuels, improve energy security, and decarbonize the energy system (IEA, 2022). Biomass-based hydrogen generation, however, faces technological and economic challenges stemming from low efficiency and impurity issues (Hamedani Rajabi *et al.*, 2016). Section 2.3 of Chapter 4 provides an in-depth description of the available hydrogen technologies.

1.2 Energy system models

Even though adopting renewable energy as a cleaner energy source may be beneficial in minimizing environmental impact, the selected energy system must be affordable and reliable. Energy system models are the most effective method for achieving the aforementioned objectives by establishing alternative scenarios under various constraints, resulting in a least-cost energy system (Pfenninger et Keirstead, 2015). Some of the models that could be used to investigate energy systems include energy system optimization or simulation models, power system and electricity market models, and qualitative or mixed methods scenarios. Energy system optimization models are used for energy policy analysis by analyzing long-term policies such as emission reduction targets and instructing energy technology policies by demonstrating the proportionate potential for various energy technologies (McDowall *et al.*, 2018). Scenario analysis is used in energy system optimization models to determine the long-term progression of energy systems (Collins *et al.*, 2017).

Mathematical decision support models are divided into two main categories. The first category takes advantage of a macroeconomic approach to model the link between energy and the economy (top-down models), and the second one employs a disaggregated approach to model energy streams while considering many substitutions and relative costs (bottom-up models).

Contrary to top-down models, bottom-up models could not demonstrate a complete picture of the economy (partial equilibrium). Although they are more suitable for systems with emerging energy sources, such as biofuels or energy technologies that are more efficient (Bahn, 2018). Bottom-up partial equilibrium energy system optimization models with a rich representation of existing and future technologies are widely used for long-term analysis of large-scale energy systems, and thus they are appropriate for long-term sustainable consideration (Volkart *et al.*, 2017). Equilibrium means that suppliers produce exactly the amount consumers seek to purchase. And partial equilibrium implies that changes in the system boundary have no effect on external sectors (Loulou, Goldstein, Kanudia, Lettila et Remme, 2016).

This study uses a partial equilibrium bottom-up model. This could be justified by the fact that bottom-up models are better suited for analyzing systems with emerging energy sources and technologies. Despite the assumption in partial equilibrium models that sectors beyond the system's boundary remain unaffected by changes within the system, these models allow for a comprehensive representation of existing and future technologies in large-scale energy systems, making them appropriate for long-term sustainable considerations. Overall, patrial equilibrium models, specifically the TIMES family, are highly suitable for informing national energy policies in long-term perspectives. These models are adept at cost optimization and are rooted in economic principles, making them capable of incorporating the impact of environmental and economic policies (Astudillo, 2019).

1.2.1 TIMES models in general

The Integrated MARKAL-EFOM System (TIMES) (Loulou, Goldstein, Kanudia, Lettila et Remme, 2016) is a bottom-up model developed within the ETSAP program of the International Energy Agency (IEA) and is used in nearly 70 countries (IEA-ETSAP, 2023). TIMES model provides valuable insights for policymakers seeking to shape long-term energy strategies (Astudillo, 2019). TIMES as a partial equilibrium model generator is placed in the class of dynamic linear programming models and includes all the different energy technologies in terms of capital cost, operation cost, efficiency, total capacity and associated GHG emissions, the different end users with final demands. The cost of producing energy for the final demands is minimized under given constraints such as GHG emission targets. It is a prospective model, i.e. it is calibrated for a reference year (e.g. 2016) and then final demands and constraints are estimated for future years and the model provides the optimal configuration of the future energy system (Bahn, 2018). Main outputs of TIMES include energy system configurations, energy flows, energy commodity prices, GHG emissions, capacities of technologies, energy costs and marginal emissions abatement costs. TIMES provides potential configurations for the energy system through comparing user-defined scenarios. TIMES outputs would be more reliable if the scenarios chosen corresponded to the actual situation. A reference energy scenario is defined in the absence of any policy constraints. The second scenario is then defined, and the intended constraints are introduced. The model generates various cost-effective energy systems using various technologies and fuel options. As a result, a wide range of technology options will be recognized by comparing the outcome to a reference scenario that satisfies all policy constraints and limitations at the lowest cost (R Loulou, Goldstein, Kanudia, Lettila, et al., 2016).

The TIMES model considers some assumptions for simplification, such as perfect competition in the energy market, which leads to the optimal solution (maximizing the total surplus) (Bahn, 2018). One of the TIMES model's assumptions is that each energy service demand has a constant price elasticity function. Furthermore, as a linear-programming model, TIMES model can only cope with carefully designed constraints. The surplus maximization objective is first transformed into an equivalent cost minimization objective by taking the negative of the surplus and calling this value the total system cost. The objective of TIMES is to reduce the system's total cost, which should be appropriately increased by the cost of lost demand. Every cost component is properly discounted to a user-specified year (Loulou, Goldstein, Kanudia, Lettila et Remme, 2016). Complete documentation of TIMES model is accessible to the public on ETSAP home page (IEA-ETSAP, 2023), including a comprehensive explanation of the sets, attributes, variables, and equations of the model.

1.2.2 North American TIMES Energy Model

The North American TIMES Energy Model (NATEM) follows a TIMES approach and represents the Reference Energy System (RES) of all Canadian jurisdictions, including 70 end-use demands for energy services in energy production, agriculture, commercial, industrial, residential, and transportation sectors (Vaillancourt *et al.*, 2017). NATEM covers the entire system, from providing primary resources to transforming, transporting, distributing, and converting energy into the supply of energy services (Figure 1.3). The spatial scale of NATEM covers 13 Canadian provinces and territories, with data disaggregated by sub-regions. A detailed representation of any region from NATEM could be extracted to build a harmonized model in integrated studies. NATEM is calibrated to a 2016 base year. The time horizon of NATEM is 2060 and is divided into 9 periods and 16 annual time slices. All costs are based on 2016 Canadian dollars with a 5% global yearly discount rate (Vaillancourt *et al.*, 2017).

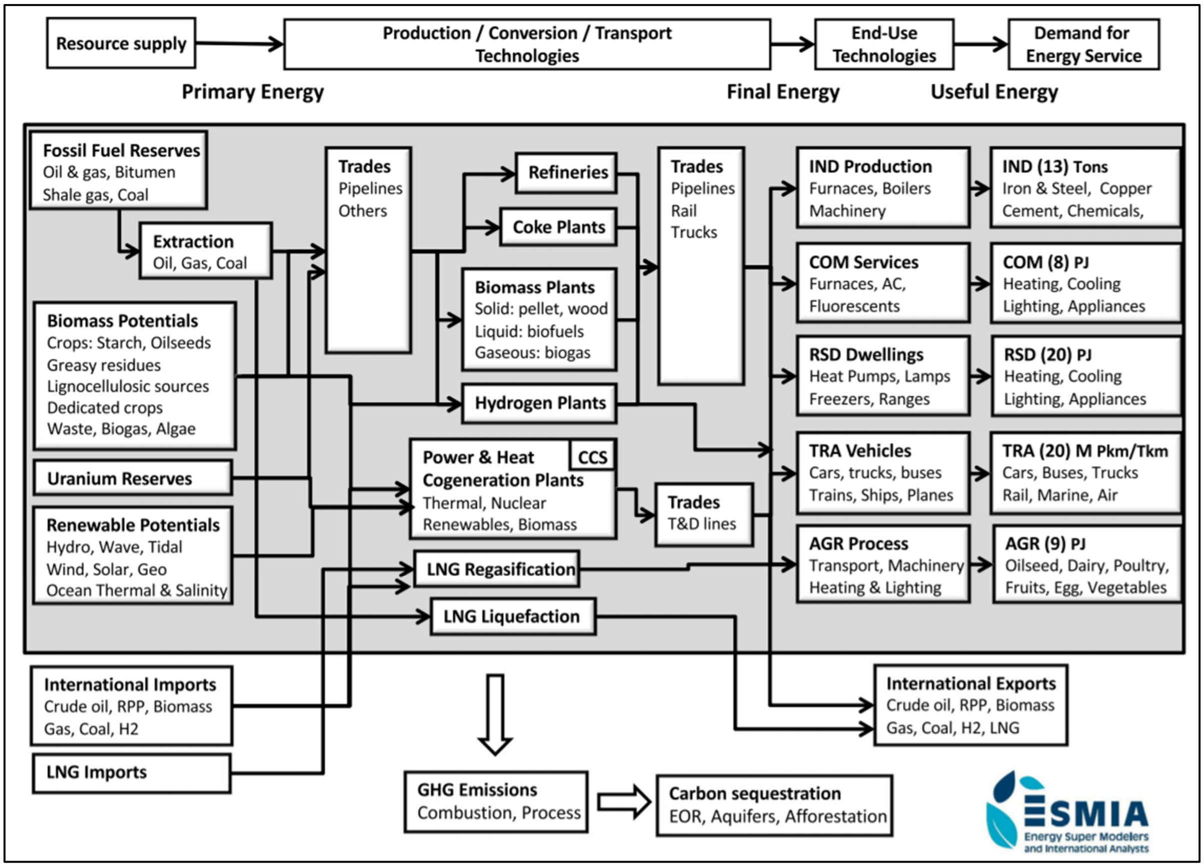

Figure 1.3 Simplified reference energy system in NATEM
Taken from Vaillancourt et al. (2014)

This study uses a comprehensive portrayal of Quebec's energy system, which is referred to as NATEM-Quebec. More than 4000 different energy technologies, 800 commodities, and 700 user constraints are included in NATEM-Quebec. Prior to this research, NATEM-Quebec included bioenergy in general (first- and second-generation biofuels), with only six lignocellulosic-based biofuels considered (Vaillancourt, Bahn et Levasseur, 2019). NATEM-Quebec also encompassed DAC, CCS, and CCU as viable NETs, alongside hydrogen production pathways. However, it does not provide a comprehensive depiction of primary and secondary forest-based bioenergy technologies, including those with and without CCS. It also lacks representation of terrestrial carbon removal and sequestration methods, such as forest management strategies, as well as the consideration of biogenic emission flows.

1.2.3 Studies in the literature using energy system models

This section presents a cutting-edge overview of the literature employing energy system models, specifically focusing on bioenergy, biogenic carbon, and hydrogen. The primary aim is to identify gaps in previous literature and address the need for further research in these areas.

1.2.3.1 Mitigating climate change with bioenergy

Bioenergy emerges as a key player in global efforts to mitigate climate change. Many studies (Börjesson *et al.*, 2014 ; Dodder *et al.*, 2015 ; König, 2011 ; Panos et Kannan, 2016 ; Zhao *et al.*, 2015 ; Jåstad *et al.*, 2021) have used energy system models such as TIMES to examine the role of bioenergy while taking into account market competition among different pathways, but they usually do not consider the dynamics of soil organic carbon and land use (Frank *et al.*, 2015) and follow a carbon neutrality assumption. For instance, Hugues, Assoumou et Maizi (2016) have used the TIMES-FR model to investigate the French bioenergy sector penetration under GHG emission constraints. Levasseur et al. (2017) used NATEM in parallel with a life cycle assessment (LCA) method to investigate environmental impacts and market penetration of butanol production from pre-hydrolyzate in a Canadian Kraft dissolving pulp mill. Vaillancourt, Bahn et Levasseur (2019) studied the potential penetration of bioenergy in Quebec by 2030 under different GHG emission reduction scenarios using NATEM-Quebec. This work focused on bioenergy, encompassing both first- and second-generation biofuels, with a limited scope of lignocellulosic-based biofuels.

1.2.3.2 Status regarding biogenic carbon

As discussed in the previous section, many research efforts have employed energy system models to address the role of bioenergy or BECCS, following a carbon neutrality assumption. Several studies (Baker *et al.*, 2019 ; Kim *et al.*, 2018 ; Favero, Daigneault, *et al.*, 2023 ; Favero, Baker, *et al.*, 2023 ; Favero, Daigneault et Sohngen, 2020) have utilized the global timber model, a partial equilibrium model designed to optimize overall welfare in timber markets, to analyze the connection between long-term changes in biomass demand and carbon sequestration. Funk et al. (2022) used a combination of GLOBIOM, a bottom-up partial equilibrium model for the agriculture, forestry, and bioenergy sectors, and carbon flux data from the NASA Carbon Monitoring System to investigate the magnitude and risks of unaccounted emissions, with a specific emphasis on the demand for wood pellets. However, the two models were not combined into an integrated approach. TIMES-MIRET, a partial-equilibrium model, has been used in combination with a dynamic biogenic carbon modeling tool to conduct a consequential life cycle assessment (LCA) of policy-driven transportation strategies for France (Albers *et al.*, 2019). In this case, the dynamic biogenic carbon modeling tool was used separately to calculate the biogenic carbon inventory of the biomass resources with long rotation lengths that had previously been fed into TIMES-MIRET. TIMES model has also been used combined with an environmentally extended input-output model to estimate indirect CO_2 emissions (Daly *et al.*, 2015), as well as LCA to fully assess the environmental impact of the energy system (Fernández Astudillo *et al.*, 2019).

1.2.3.3 The rising significance of hydrogen in the energy transition

Several studies have been conducted to assess the role of hydrogen in climate change mitigation using energy system models. Research conducted using Energy-Environment-Economy (E3) models offers valuable insights into determining the most economically advantageous pathways towards achieving full decarbonization. These studies not only focus on the integration of hydrogen technologies but also consider alternative options such as bioenergy, carbon capture, and direct electrification technologies. By analyzing various combinations of these technologies, researchers can identify the optimal approaches for achieving net zero emissions. Many research projects look at hydrogen more specifically, using E3 models in the TIMES family. However, these studies ignore GHG emissions and uptakes associated with forest management and BECCS and follow a carbon neutrality assumption. For instance, Blanco et al. (2018) used the JRC-EU-TIMES model to assess the role of hydrogen and synthetic liquid fuels in the European GHG reduction strategy. The results show that factors with the largest impact are the GHG reduction target, biomass, and geologic CO_2 sequestration availability. Espegren et al., (2021) assessed the role of hydrogen in Norway's energy transition using three analytical perspectives, including an energy systems perspective with a TIMES model. Renewable energy and hydrogen were identified as essential components in decarbonizing Norwegian transportation and industrial sectors. Yang et al. (2022) used a TIMES-based energy system optimization model (China-MAPLE) to investigate the role of hydrogen in difficult-to-decarbonize sectors of heavy industries and heavy-duty transportation in China. According to the findings, clean hydrogen can be used as an energy carrier and feedstock in decarbonizing heavy industry, as well as a fuel for up to half of the Chinese transportation sector. Using TIAM-ECN, a TIMES-based model, van der Zwaan et al. (2021) investigated the export of electricity and hydrogen from North Africa to Europe. They found solar power could be produced in significant quantities in North Africa and economically transmitted to Europe, or it could be converted to hydrogen via electrolysis and transported to the Eurozone via pipeline. In the Net-Zero America study (Larson *et al.*, 2021), hydrogen plays a significant role in seasonally balancing the grid in 2050, through intermittent electrolysis, intermittent hydrogen steam boilers (alternating with electrical ones), and hydrogen use in natural gas power plants, across all net zero scenarios. The largest part of hydrogen, however, is produced via biomass gasification with CO_2 capture and storage (BECCS) in most net zero scenarios. Electrofuel production is a major consumer of hydrogen only in scenarios restricting direct electrification or CO_2 storage. The International Energy Agency Net Zero by 2050 Roadmap (IEA, 2021), using the WEM and ETP models, finds comparable uses of hydrogen, with more emphasis on direct use of hydrogen and ammonia as transportation fuels, while biomass is directed more towards solid fuel applications. BECCS is entirely absent as a source of hydrogen; it is not specified if that is because the technology is absent from the model, because the optimizer selected against it, or because the different geography and policy aspects of the model penalize it. In another example, a study done for Quebec (Dunsky et ESMIA, 2021), using a variant of NATEM, arrives at a somewhat limited use of hydrogen in the context of the hydroelectricity-rich province. It is produced entirely using BECCS, serves primarily the industrial and transportation sectors, and is presented more as an economic source of negative emissions than as an important replacement fuel. Interestingly, two scenarios that respectively allow and deny negative emissions, but are otherwise nearly identical in their input assumptions, show a major shift as to whether biomass should optimally be allocated to produce hydrogen or liquid fuels. Overall, there is a significant disagreement between studies about the extent to which hydrogen is necessary or useful to fully decarbonize at the lowest possible cost, and the ongoing development of E3 models might help guide investment decisions and the efficient allocation of scarce renewable resources such as forest- based residue.

Previous research papers have studied the role of hydrogen toward a net-zero economy. However, a comprehensive analysis of the role of hydrogen in achieving full decarbonization in the regional context of Quebec, Canada has been lacking, particularly when considering biogenic emission flows. Additionally, the role of hydrogen utilization compared to alternative technologies such as bioenergy, carbon capture, and direct electrification within the province remains unanswered.

1.3 Forest-based bioenergy production pathways

This section provides an overview of common and emerging lignocellulosic-based bioenergy conversion technologies. These technologies convert biomass into three primary outputs: electricity and heat as energy outputs and chemical feedstock as non-energy output. There are two types of conversion technologies: thermochemical and bio-chemical/biological. Furthermore, mechanical conversion is considered a primitive conversion technology for converting biomass to energy (McKendry, 2002). The reference energy system of common and emerging conversion technologies for producing lignocellulosic-based bioenergy is depicted in Figure 1.4. This figure has been developed as part of the first specific objective of this thesis. It shows the flow of resources, production, and conversion applications to end-use technologies.

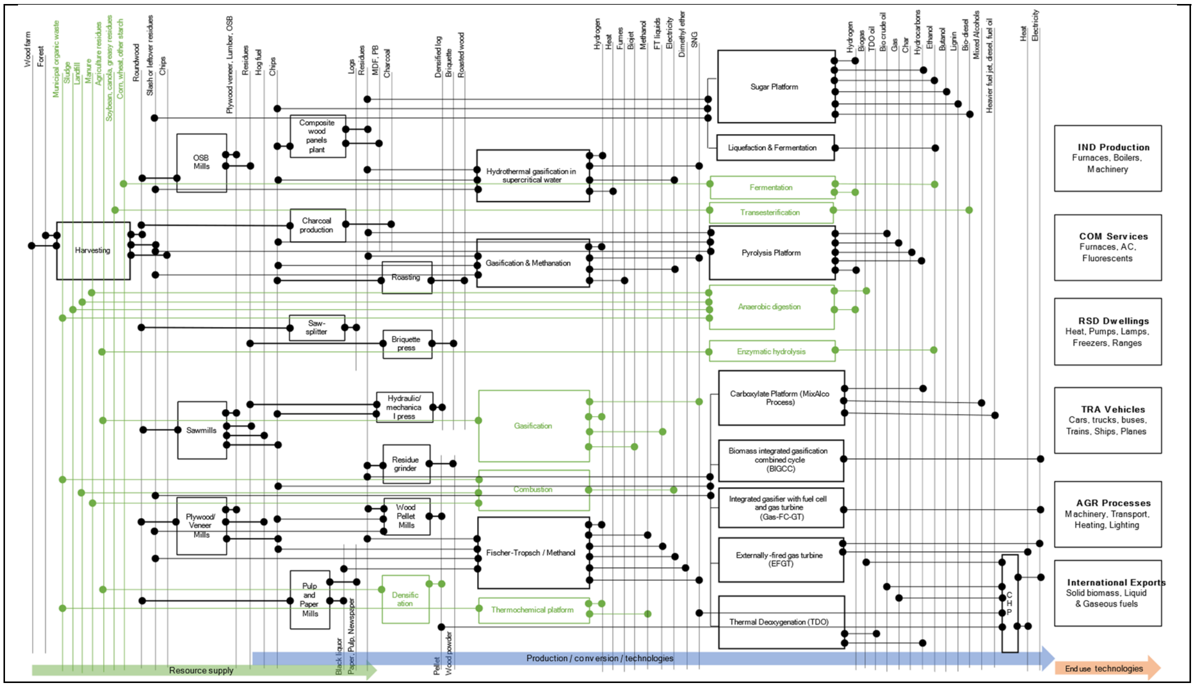

Figure 1.4 Emerging forest-based bioenergy conversion processes (in black) compared to the first-generation bioenergy conversion processes (in green).

1.3.1 Mechanical conversion processes

Mechanical conversion processes of forest-based biomass primarily include splitting, chipping, pressing, and grinding, yielding in solid fuels such as logs, densified wood logs, wood pellets, wood chips, and wood powder.

1.3.1.1 Wood chips

Wood chips are produced from branches and treetops left over after logging and pruning, trees with no other material value, as well cultivation of trees for energy usage. Woody materials are shredded in the forest by a waste woodchipper or on a mobile chipper platform. The calorific value of wood chips is around 2500-3500 kW/tonne, depending on the moisture content of the feedstock. Wood chips are mainly used as a fuel for furnaces or industrial furnaces and as a cogeneration of heat and power (Douard, 2010).

1.3.1.2 Wood Pellets

Wood pellets are the most processed product in mechanical conversion. Pellets generally produce from sawdust and finely ground wood through compressing in the granulation factory. The calorific value of wood pellets is about 4700 kW/tonne. Whereas its energy content could be enhanced from 9 to 18 MJ/m^3 by torrefaction of feedstock (Douard, 2010 ; Guo, Song et Buhain, 2015). Torrefaction is used as the feedstock pretreatment through pyrolysis at a relatively low temperature of 225–300 °C. Hemicelluloses and wood lignin are decomposed, followed by somewhat dehydrogenation (chemical removal of water). As a result, it enhances the calorific value and density of pellets (Caillat et Vakkilainen, 2013). The primary applications of pellets are in wood stoves or automatic furnaces (Douard, 2010).

1.3.2 Thermochemical Conversion Processes

Thermochemical conversion processes are divided into four main categories: combustion, gasification, pyrolysis, and hydrothermal liquefaction. In addition, charcoal production and roasting are considered thermochemical conversion technologies that produce charcoal, briquette, and roasted wood.

1.3.2.1 Combustion

Combustion is defined as converting the chemical energy of biomass into heat/mechanical power/electricity by burning biomass in the presence of air through different means such as stoves, furnaces, boilers, steam turbines, turbo-generators, etc. Any type of biomass with a moisture content below 50% is suitable for combustion unless the biomass is pre-dried. Biomass with high moisture content is more favorable for biological conversion processes. The scale of the combustion plant varies from 100 to 3000 MW. The conversion efficiency for biomass combustion power plants is about 20-40%. However, higher efficiencies are gained in power plants over 100 MW or co-firing of biomass with coal, which is 33–37% (Guo, Song et Buhain, 2015 ; McKendry, 2002).

1.3.2.2 Co-firing

Co-firing biomass in coal-fired power plants is an efficient route utilized by several coal-fired power plants to generate electricity on a commercial scale (McKendry, 2002). For instance, wood chips could be combusted in a 15-30% volume blended with pulverized coal to produce steam turbines (Guo, Song et Buhain, 2015).

1.3.2.3 Combined Heat and Power (CHP)

Combined heat and power (CHP) systems are broadly utilized in the industrial, household, and service sectors to supply required heat for process and space, hot water, and electricity (Kahlert et Spliethoff, 2017). The CHP cycles can consume various biomass-based fuels, including wood pellets, bio-oils, and synthesis gases.

1.3.2.4 Gasification

The gasification conversion process by partial combustion of biomass produces a gaseous stream – known as synthesis gas (SNG) - of carbon monoxide, carbon dioxide, hydrogen, methane, and water, besides unwanted residual tars and chars. Gasification tends to maximize the efficiency of SNG output by minimizing the number of condensable hydrocarbons and unreacted char. The proportion of SNG relies upon the feedstock type, feed ratios, process parameters, and gasifier type. The energy density of SNG is about half of the natural gas (CH_4) applicable in the steam cycles, gas engines, fuel cells, or turbines to generate power and heat. SNG plays an intermediate role in producing liquid fuels and other bio-chemicals, such as hydrogen, synthetic natural gas, naphtha, kerosene, diesel, methanol, dimethyl ether, and ammonia. It can be transformed into alcohols and/or hydrocarbons (HCs) using fermentation or chemical catalytic methods (Ibarra-Gonzalez et Rong, 2018 ; Van Walsum et Wheeler, 2013).

1.3.2.5 Gasification and Methanation

As an emerging thermochemical process, this pathway generates synthetic natural gas (SNG), a mixture of CH_4, H_2, CO, CO_2, and H_2O from lignocellulosic resources. In addition, a schematic illustration of the process is presented in Figure 1.5. As can be seen, a drying step is required before the gasification process for raw material's moisture content reduction below 20 %. The gasification step converts the biomass into SNG at 800-900 ˚C in an oxygen-restrained environment. The syngas is then cleansed before being converted to SNG by the methanation process in a catalytic reactor (using nickel catalysts) at 300-400 ˚C. Depending on the biomass composition and the specific gasification technology, the reactor output will contain between 40 and 50% of methane (CH_4), which should be separated from the CO_2 and the remaining H_2 for injecting into the natural gas grid. The energy output of SNG per energy input of biomass shows the fuel efficiency of the technology, which is around 39 to 75%, regarding the biomass composition and humidity. The feasibility of this polygeneration process has been proven on a pilot scale (1 MWSNG) in Guessing, Austria. A commercial-scale plant with a capacity of a hundred MWSNG in Göteborg, Sweden, envisions by 2020 (Codina Gironès, 2018).

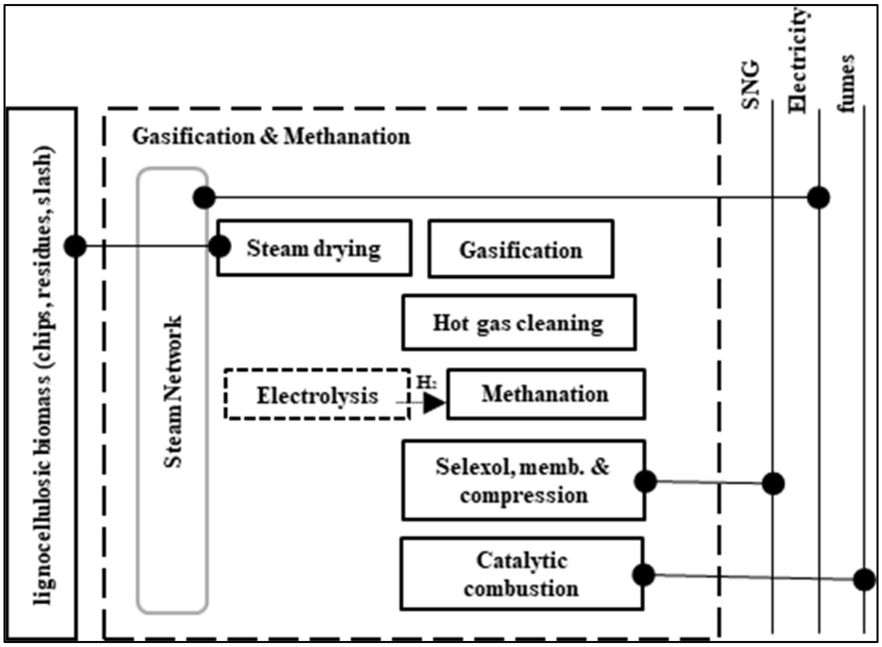

Figure 1.5 Gasification and Methanation

1.3.2.6 Fischer-Tropsch / Methanol

The thermochemical conversion of biomass to synthetic fuels is known as biomass-to-liquid (BtL). The ultimate aim of BtL technology is to replace petroleum products by producing non-polluting biofuels similar to those of fossil-derived fuels, accordingly, usable in fuel distribution systems and standard engines (Ibarra-Gonzalez et Rong, 2018). The Fischer-Tropsch (FT) process (Figure 1.6), as a BtL technology, is proficient in producing liquid hydrocarbon fuels from SNG, which has been claimed to be a carbon-neutral substitution for petroleum products in recent studies. The global interest in FT synthesis is mainly due to the increased environmental impacts of natural gas consumption in remote locations and technological developments. FT-liquids are free of sulfur and contain very few aromatics compared to gasoline and diesel, which results in lower emission levels when applied in internal combustion engines (Tijmensen *et al.*, 2002).

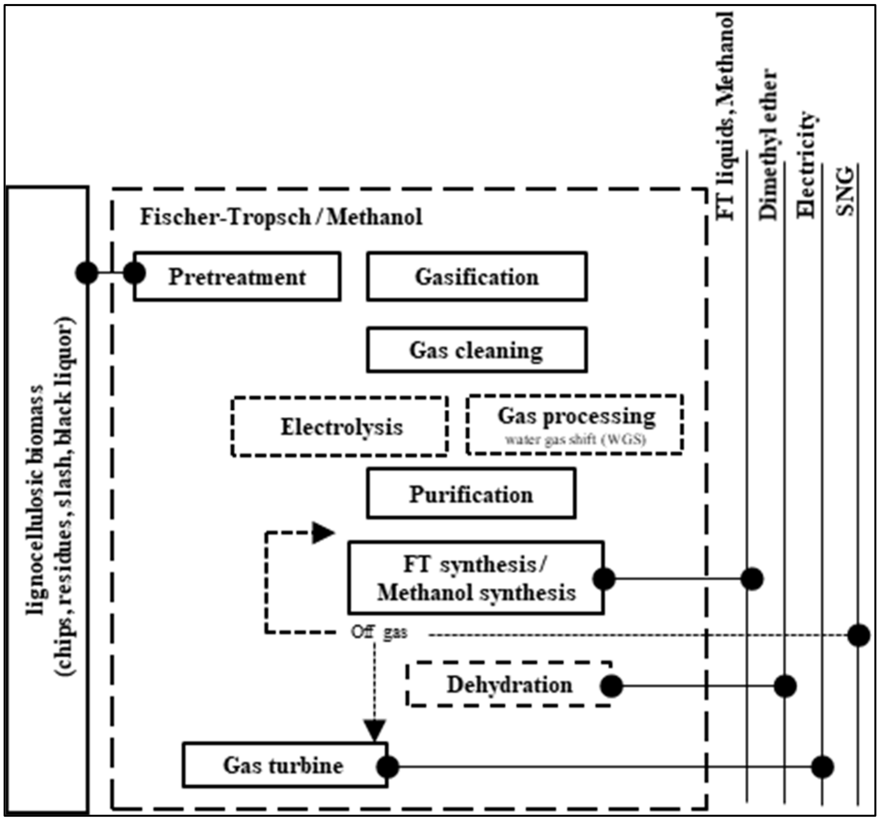

Figure 1.6 Fischer-Tropsch / Methanol

Besides, Methanol (CH_3OH), also known as methyl alcohol or wood alcohol, is usable as a fuel, either as a blend with gasoline in internal combustion engines or fuel cell vehicles. In addition, Methanol is a functional product in the chemical industry as a starting point for many chemicals. Lignocellulosic-based Methanol could be a feasible way to address several problems related to the current use of petroleum-derived fuels, such as energy security and GHG emissions (Hamelinck et Faaij, 2002).

Lignocellulosic biomass is dried, torrefied, and ground into fine particles in pretreatment. The biomass particles are then transmitted into a pressurized (30 bar) steam-oxygen blown entrained flow gasifier. H_2, CO, and CO_2 are the primary gases produced as SNG in the gasifier. SNG is cooled by a water quench and cleaned in a scrubber. A water gas shift (WGS) reactor is adopted to adjust the H_2 to CO ratio. CO_2 is excluded by amines scrubbing to satisfy the FT synthesis needs by which the liquid hydrocarbon fuels are produced. FT-liquids can be blended with diesel fuel. In addition, the Methanol production process as another BtL conversion technology is analogous to the FT-liquid conversion pathway (Codina Gironès, 2018).

1.3.2.7 Power-to-Gas (PtG) for FT liquid fuel production

Steam electrolysis could be applied to supply the required hydrogen for desired H_2/CO_2 ratio as a substitution for the water gas shift reaction in the FT process. Enhancing the H_2 portion increases carbon content, consequently boosting liquid fuel production. Essentially, the use of H_2 from electrolysis lead to a long-term storage option for excess renewable electricity in all conversion processes. The steam electrolysis improves the energy content per unit of biogenic carbon in the input. Energy content is changed from 13.4 MJ_{LHV}/kgC_{input} for the process with the water gas shift reaction to 26.1 MJ_{LHV}/kgC_{input} for the process with the electrolysis (Codina Gironès, 2018).

1.3.2.8 Hydrothermal Gasification in Supercritical Water

Unlike the gasification and methanation process, hydrothermal gasification (HTG) is suitable for converting lignocellulosic biomass with high moisture content (more than 50%) to SNG. As shown in Figure 1.7, electricity and heat as co-products can be derived from adding a combustion or CHP sector. The notable dominance of this technology over other conversion processes is that lignocellulosic biomass is treated in supercritical water (a temperature and pressure above the critical point of water that is 373.946 °C and 217.7 atm, respectively (Purdue-University, 2023). Therefore, energy consumption in the drying phase would be avoided (Codina Gironès, 2018). After hydrolysis and salt separation, lignocellulosic biomass is gasified into primary H_2 and CH_4 as burnable gases and CO_2 without adding a solid catalyst or in the presence of carbon or other solid catalysts (Kruse, 2009).

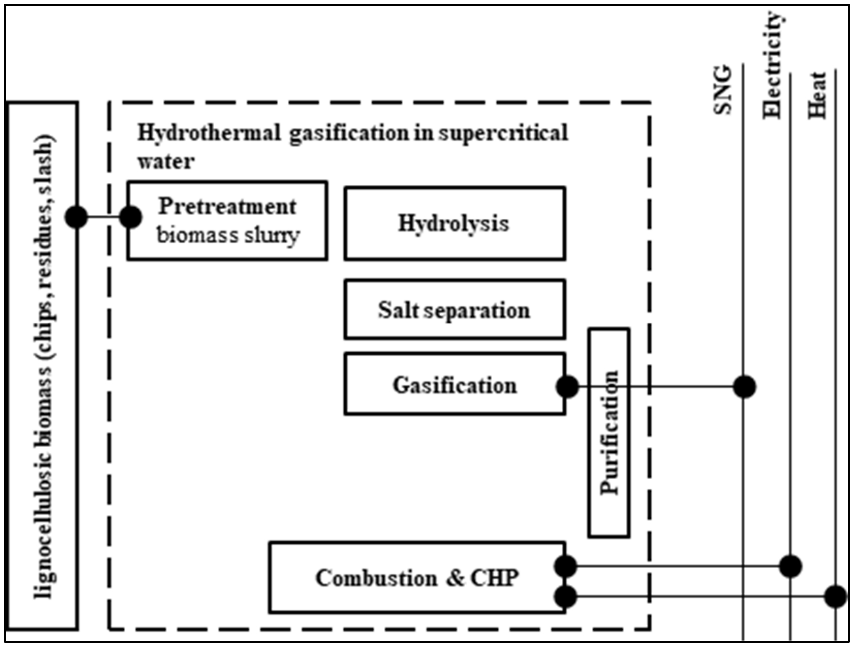

Figure 1.7 Hydrothermal gasification in supercritical water

It should be noted that supercritical conditions need less energy to heat up the water to the operating state. There is no commercial scale of this emerging technology, and only the lab scale of the HTG conversion process has been introduced. The efficiency of the HTG process is directly related to the feedstock's characteristics. Furthermore, the process heat demand is quite sensitive to the dilution of the organic matter in the water. Respectively, HTG is in direct competition with anaerobic digestion. Indeed, these two conversion processes complement each other since HTG can treat in a post-process the non-digested output from the digestion reactor (Codina Gironès, 2018).

1.3.2.9 Hydrothermal Liquefaction

Liquefaction was initially developed for converting coal into liquid fuels. Despite the utilization of direct liquefaction as a conversion process for various lignocellulosic materials, such as forest-based biomass, agricultural residues, aquatic plants, and organic residues, there are currently no direct liquefaction processes implemented on a commercial scale (Ibarra-Gonzalez et Rong, 2018). Hydrothermal processing can be divided into three separate processes regarding the intensity of temperature: hydrothermal carbonization (HTC), which works at temperatures below 520 K. The primary output is hydrochar which is similar to low-rank coal. At the temperature ranges between 520 K and 647 K, the process is called hydrothermal liquefaction (HTL), which produces a liquid fuel known as biocrude. Biocrude is comparable to crude oil and can upgrade to the whole distillate range of petroleum-derived fuel products. Third, temperatures above 647 K switch gasification reactions on, and the process is identified as hydrothermal gasification (HTG), resulting in the production of synthetic fuel gas (SNG) discussed in the gasification section. The lower amount of organic carbon found in the water phase of HTG following the gasification step leads to high carbon efficiencies. This considers the main preference over HTL technology. The objective in all mentioned cases is to produce an output with a higher energy density by oxygen elimination. HTL of biomass is considered a thermochemical conversion of biomass to produce liquid fuels by processing in a hot, pressurized water environment for enough time to decompose the solid biopolymeric structure into primarily liquid ingredients (Elliott *et al.*, 2015).

Pretreatment is needed for lignocellulosic biomass to reduce the particle size, remove the contaminants, and alkaline treatment to obtain a stable slurry for easy pumping. A catalyst is expected to enhance the product's bio-oil efficiency and quality. After feedstock processing through HTL, a gaseous stream of CO_2, solid residue (char), bio-oil, and small traces of aqueous phase containing soluble organic compounds will be separated by separation steps. HTL bio-oils are semi-liquid and very viscous. Complicated mechanisms, a high percentage of oxygen, and undesirable solids make the HTL process difficult to operate and achieve a suitable fuel with liquid fuel standards (Ahmad, Silva et Varesche, 2018 ; Ibarra-Gonzalez et Rong, 2018).

1.3.2.10 Pyrolysis

Pyrolysis as a thermochemical conversion process transforms lignocellulosic biomass into various molecular arrangements in the absence of O_2 and produces char as solid, bio-oil as liquid, and gasses bioenergy (Figure 1.8) (Van Walsum et Wheeler, 2013). The pyrolysis process could be divided into three categories: catalytic, fast, and flash. The major process characteristics that make a difference between pyrolysis categories are the solid residence times, heating rate, particle size, and temperature (McKendry, 2002). Making the conversion process faster will produce more oils; in contrast, letting the conversion process done slower will generate more char and gasses. Obviously, to produce liquid fuels, the oils are the desired output, which needs deep commitment to exploring feasible ways to maximize oil yield and quality from fast pyrolysis. Most existing conversion processes consider applying catalysts and added H_2 to upgrade the quality of the bio-oil to be compatible with the fuel properties of the current transportation system (Van Walsum et Wheeler, 2013).

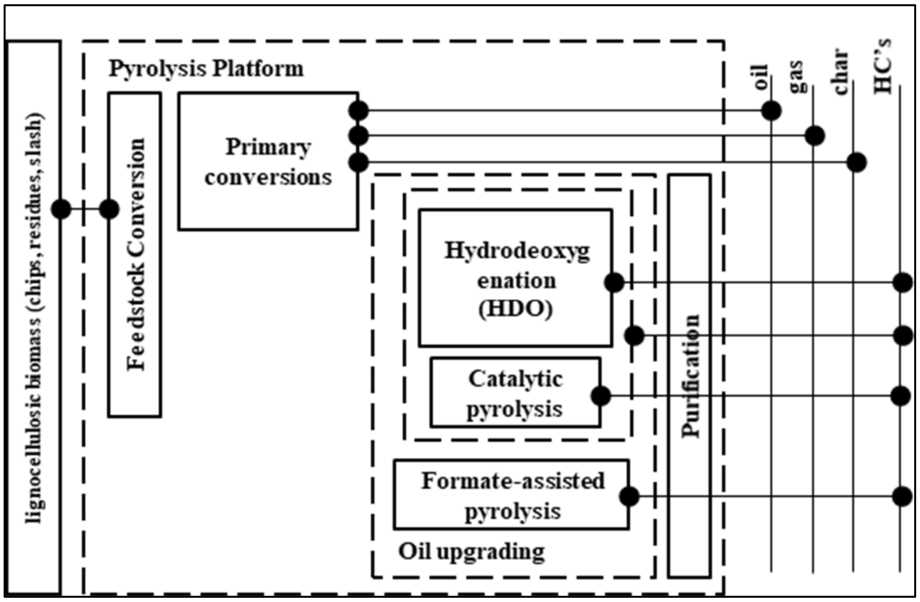

Figure 1.8 Pyrolysis

The feedstock composition has a considerable effect on the output yields and quality. For example, oxygen rate and heating values in the bio-oils derived from forest-based biomass are higher and lower than bio-oils produced from agricultural-based biomass -which contain more hydrocarbon-like starting components-respectively. Char separation from the pyrolysis vapors and rapidly quenching polymerization reactions by condensing the vapors are required in all pyrolysis technologies, which could be challenging given they are primarily aerosols.

Furthermore, it would be necessary for all of the pyrolysis methods to enhance the quality of the oil by decreasing oxygen and water content and raising energy density and shelf life. The mentioned requirements could be dealt with through catalytic upgrading and hydrotreatment methods. Upgrading pyrolysis bio-oil to a usable transport fuel like diesel, gasoline, kerosene, and by-products needs full deoxygenation and some conventional refining, which could be done either by Hydrodeoxygenation (HDO) or by catalytic cracking. In addition, blending the lignocellulosic biomass with a divalent formate alkali salt, such as calcium formate, could be another upgrade option (Van Walsum et Wheeler, 2013 ; Ibarra-Gonzalez et Rong, 2018).

1.3.3 Biochemical conversion processes

Anaerobic digestion and fermentation are two primary biochemical conversion processes.

1.3.3.1 Anaerobic digestion

The conversion of organic biomass directly to a gas (biogas) is known as the anaerobic digestion process. Biogas consists primarily of CH_4 and CO_2, with small amounts of other gases like H_2S. The biomass is decomposed by bacteria in an anaerobic reactor, producing a gas with an energy content of around 20–40% of the lower heating value of the feedstock. Anaerobic digestion is vastly applied for treating high moisture content organic wastes (more than 80–90%) commercially. Biogas is usable in spark ignition gas engines or gas turbines as a direct fuel. The properties of biogas could be enhanced (comparable with natural gas) by eliminating carbon dioxide (McKendry, 2002). Lignocellulosic biomass is potentially a very available feedstock for methane production. A complicated structure and a deficiency of suitable digester reactors designed to effectively treat high-solid biomass are the main issues in the anaerobic digestion of lignocellulosic biomass (Sawatdeenarunat *et al.*, 2015).

1.3.3.2 Fermentation

The carbohydrate content of the lignocellulose forest-based biomass is the starting material for conversion to biofuels. The sugar derived from lignocellulose after hydrolyzation is transformed into glucose, xylose, arabinose, mannose, and galactose in different proportions biologically using the fermentation process of the cellulose and hemicellulose fractions of the wood after (Figure 1.9).

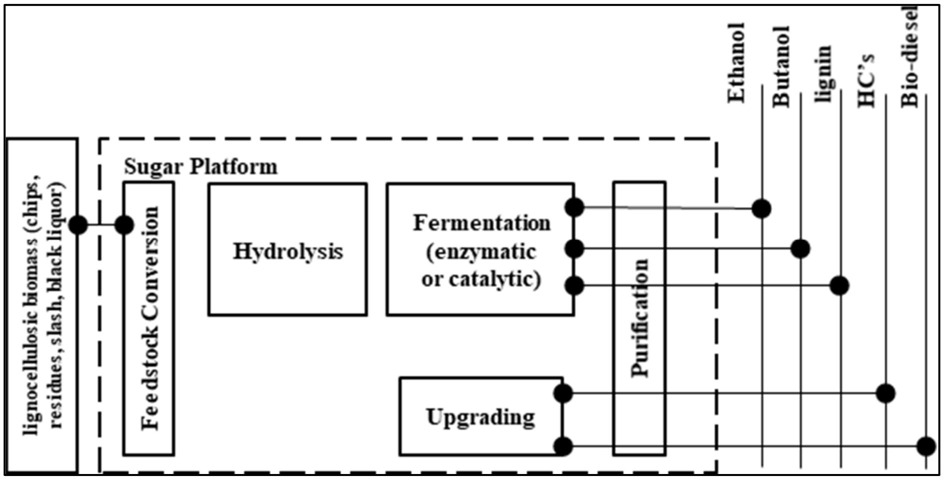

Figure 1.9 Fermentation

The fermentation conversion process has been broadly applied to produce ethanol from corn. The main issue of alcohols producing from lignocellulosic biomass is dealing with the high hydrolysis phase cost. The fermentation method cannot convert the wood's lignin content to bio-oil. Consequently, the lignin is used for internal operations as the boiler fuel or sale as a co-product. Ethanol and butanol as fermentation products are compatible with spark-ignited engines. Ethanol derived from starch or sugar, and ethanol from lignocellulose are identified as "first-generation" and "second-generation" biofuels, respectively. Butanol is known as an "advanced" biofuel because it can be mixed at any ratio with gasoline. However, it is not considered a "drop-in" fuel because butanol energy density is lower than gasoline (Van Walsum et Wheeler, 2013).

1.3.4 Hybrid platforms

Hybrid platforms are dedicated to conversion processes that integrate thermochemical and biochemical processes. The Carboxylate platform (MixAlco Process), thermal deoxygenation (TDO), liquefaction, and fermentation are summarized here.

1.3.4.1 Thermal Deoxygenation (TDO)

The organic acids produced from lignocellulosic biomass using acid-catalyzed hydrolysis and dehydration are neutralized to carboxylate salts, ketonized to mixed ketones and hydrocarbons, and consequently hydrotreated to generate thermal deoxygenation (TDO) oils (Figure 1.10). The TDO oils and distillate fractions produced from them are compatible with diesel and spark ignition engines, respectively. Although, hydrotreatment with a nickel catalyst is used to further improve the fuel properties (Van Walsum et Wheeler, 2013).

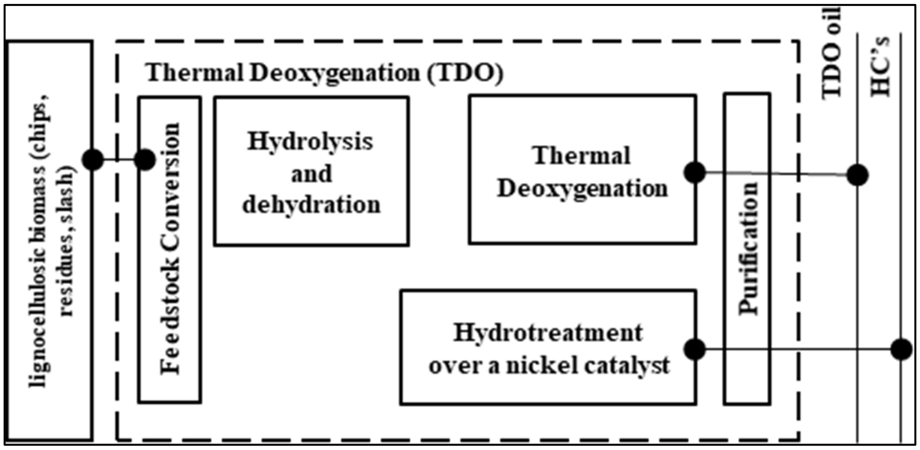

Figure 1.10 Thermal deoxygenation (TDO)

1.3.4.2 Carboxylate platform (MixAlco Process)

Carboxylate platforms (MixAlco Process) digest lignocellulosic materials by anaerobic organisms and then converts metabolic products to ketones and oils by pyrolysis that is upgradable to liquid fuels (Figure 1.11). Mixed alcohols are more stable compared to the liquid fermentation fuels that are very susceptible to contamination. Acidogenic digestion works as a substitution for the fermentation conversion process that uses mixed cultures of organisms cultivated under conditions that result in the accumulation of organic acids. The approach is similar to biogas production by anaerobic digestion; however, to accumulate organic acids, growing methanogenic organisms is prohibited. Therefore, organic acids are used as a feedstock to produce organic chemicals or biofuels through chemical conversions. Oxygen content in carboxylic acids is relatively high for current transportation systems. Two methods to decrease oxygen content are adding hydrogen to remove oxygen as water (esterification) or sacrificing carbon atoms to release oxygen as carbon dioxide (ketonization) (Van Walsum et Wheeler, 2013).

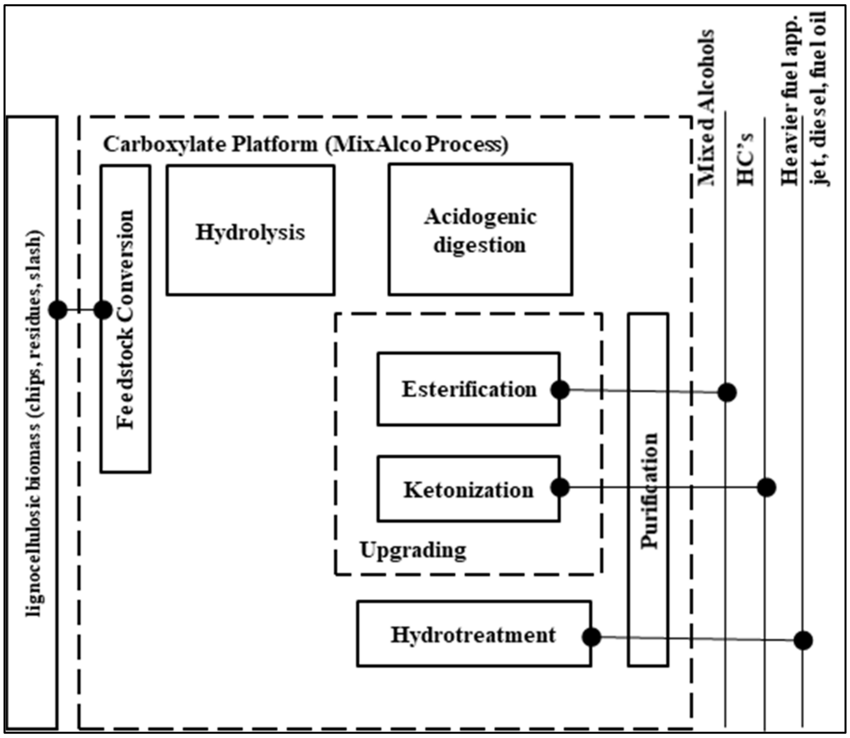

Figure 1.11 Carboxylate platform (MixAlco Process)

The ketonization approach consumes less H_2 than the esterification method, decreasing the bio-oils carbon yield. The net chemical energy balance between the upgrading approaches is the same. Producing longer carbon chain alcohols in the ketonization approach makes the output fuel more like hydrocarbon fuels (HCs). The Mixed alcohol is hydrotreated to produce fully deoxygenated hydrocarbons suitable for heavier fuel utilization, for instance, jets, diesel, and fuel oil (Van Walsum et Wheeler, 2013).

1.3.4.3 Liquefaction and Fermentation

This process treats lignocellulosic biomass with solvents and acids, decompose the treated materials into fermentable sugars through solvent liquefaction, and ferments the sugars to produce ethanol (Figure 1.12). The pretreatment reactor works at a temperature of 120 °C. A separation sector separates vapor with 99.93% of the solvent, xylose-rich liquid sugar, and solids stream with mostly lignin. The lignin could be burned in a boiler for heat and power, whereas the solvent is recycled. The cellulose-rich pulp slurry is transmitted to a liquefaction reactor to decompose into sugars. The sugar-rich streams undergo hydrolysis to transform the remaining anhydrosugars into hydrosugars favorable to fermentation. Ethanol is produced at 92% purity following distillation columns and can be dehydrated to 99.5% via vapor-phase molecular sieve adsorption (Li *et al.*, 2018).

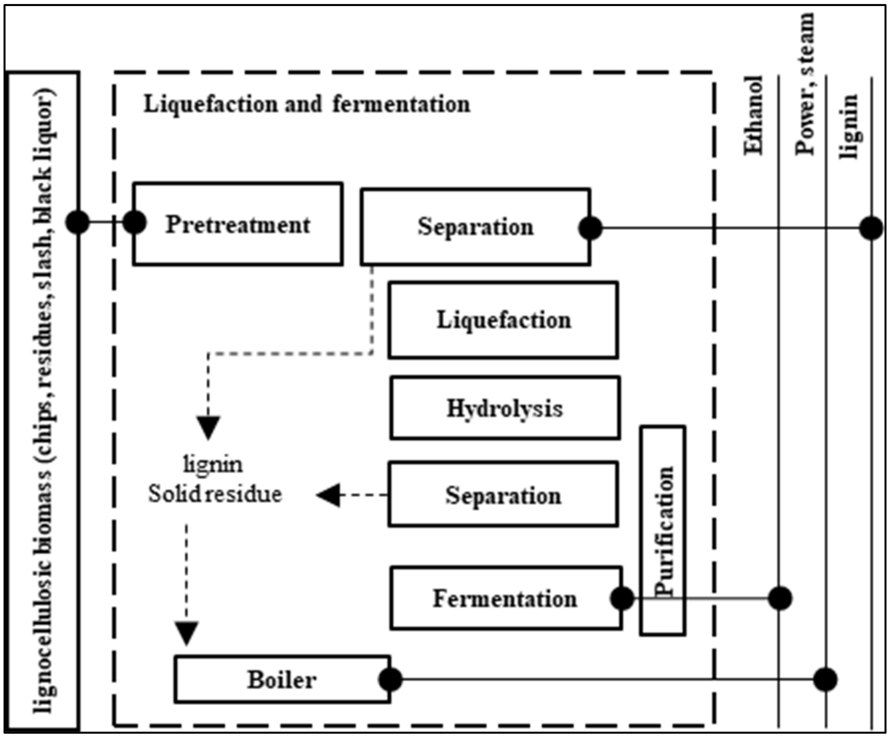

Figure 1.12 Liquefaction and fermentation

1.3.5 Other combined cycles

In this section, other conversion processes that primarily generate heat and electricity are briefly discussed. One such process is the Biomass Integrated Gasification Combined Cycle (BIGCC), where lignocellulosic biomass is converted to synthetic natural gas (SNG) in a pressurized gasifier. The SNG is then purified before entering a gas turbine, which generates electricity (Codina Gironès, 2018). Another process is the Integrated Gasifier with Fuel Cell and Gas Turbine (Gas-FC-GT), which involves transforming lignocellulosic biomass into SNG in a gasifier. The purified SNG then enters a Solid Oxide Fuel Cell and a gas turbine to generate electricity (Codina Gironès, 2018). Additionally, the Externally Fired Gas Turbine (EFGT) technology is introduced as a new approach for small and medium-scale power and heat generation. This method improves efficiency by recycling waste heat from turbines and allows the use of "dirty" fuels. EFGT presents a promising solution for utilizing biomass in combined heat and power applications while mitigating greenhouse gas emissions (Kautz et Hansen, 2007).

1.4 Biogenic carbon

This section focuses on the assumption of biogenic carbon neutrality and its limitations, modeling forest carbon in national GHG emission inventories using CBM-CFS3, and the assessment of various forest management scenarios in Quebec. Additionally, the section explores the inclusion of biogenic carbon in the TIMES model, highlighting the importance of integrating it and emphasizing its significance as a valuable contribution to the thesis.

1.4.1 Biogenic carbon neutrality assumption

Carbon that is taken up, sequestered, or released by biomass is known as biogenic carbon (Figure 1.13) (Berndes *et al.*, 2016). Biogenic CO_2 emissions from bioenergy sources, according to the IPCC (Eggleston *et al.*, 2006), should not be included in the energy sector of national greenhouse gas inventories since all biogenic emissions and uptakes are accounted for in AFOLU sector. Accordingly, government initiatives endorse bioenergy as an alternative carbon-neutral energy source for fossil fuels (Liu *et al.*, 2017). This could lead to accounting errors in jurisdictions where carbon flows from the AFOLU sector are not included in GHG emissions inventories. Governments also rely on energy system models to explore potential decarbonization pathways. The carbon neutrality assumption might be acceptable when the rotation length of biomass is short such as annual crops. The assumption, however, may not remain true when the sequestration period is lengthy, as in the case of forest trees (Cherubini *et al.*, 2011 ; Guest *et al.*, 2013). Bioenergy systems can lead to positive, neutral, or negative effects on biogenic carbon stocks (Berndes *et al.*, 2016). The carbon-neutrality assumption is increasingly being questioned, with several studies indicating that it may result in accounting errors and biased decision-making (Berndes *et al.*, 2016 ; Liu *et al.*, 2017 ; Albers *et al.*, 2019).

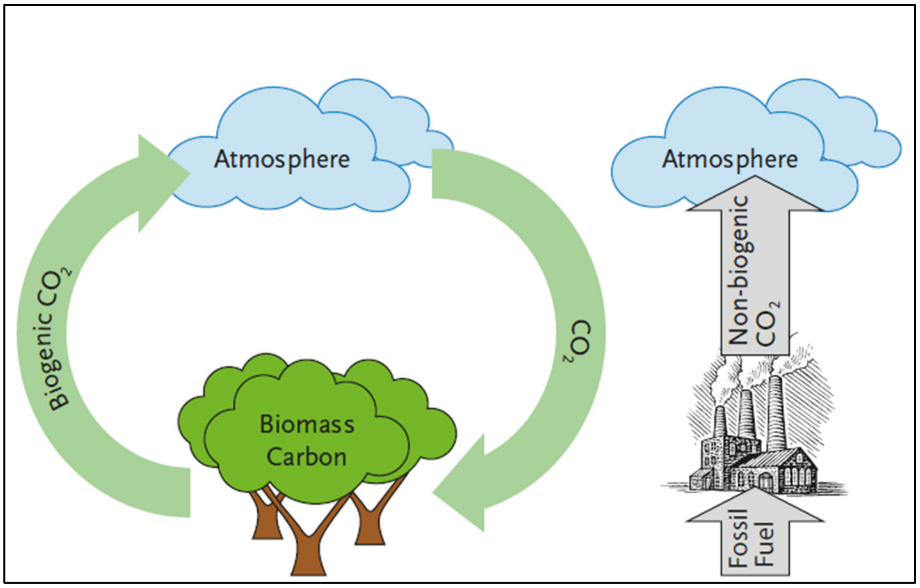

Figure 1.13 Distinction between biogenic and non-biogenic CO_2
Taken from Berndes et al. (2016)

1.4.2 Modeling forest carbon

Several studies (Head *et al.*, 2019 ; Moreau *et al.*, 2022 ; Landry *et al.*, 2021) have evaluated the role of forest management or bioenergy in climate change mitigation using modeling frameworks that simulate the dynamics of forest carbon stocks. However, these studies cannot assess the most cost-effective pathways to reduce GHG emissions. For example, Smyth et al. (2014) assessed the mitigation potential of Canadian managed forests from 2015 to 2050 using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). They considered seven forest management approaches and two harvested wood product strategies. Better utilization scenario (increasing utilization of harvested wood, maximizing salvage harvesting, avoiding burning residues, and collecting 50% of residues for bioenergy) showed the most climate change mitigation potential. Lamers et al., (2014) used CBM-CFS3 to analyze different scenarios for damaged forests of British Columbia. Using harvesting leftovers as bioenergy feedstock indicated a higher emission reduction potential than a protection reference scenario. Smyth et al. (2017) analyzed the climate change mitigation potential of local harvest residues for bioenergy in Canada using three models, including CBM-CFS3. The results suggested that the substitution of harvest residues for fossil fuels leads to GHG emission reduction. Whereas displacement of these residues for cleaner energy sources such as low-emission hydroelectricity resulted in further emissions. Cintas et al. (2017) employed a scenario-based approach, by relying on an established Swedish model, to investigate the potential role of forest management in climate change mitigation in Sweden. According to this study, the Swedish forest sector contributes to achieving carbon neutrality by offering bioenergy and other forest products. Simultaneously, it acts as a carbon sink and maintains vegetation and soils. In a study by Gustavsson et al. (2017), the Heureka Regwise simulator and the Q-model were used to investigate the climatic implications of different forest management strategies, harvest residue extraction levels, and end-use options for forest products in Sweden. A scenario with high harvest and residue recovery rates was introduced as the most promising pathway toward climate change mitigation.

The CBM-CFS3 is a model that uses inventory-based data to simulate the dynamics of carbon in forests through considering various factors such as above- and belowground biomass, dead wood, litter, and mineral soil (Kurz et al., 2009). The model has been extensively used and validated in Canada (as discussed above), Ireland (Duffy *et al.*, 2021), South Korea (Kim *et al.*, 2017), and 26 European Union member states (Pilli *et al.*, 2016). It simulates the effects of land-use change and serves as a means to account for land-use change impacts under the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol requirements and the according to IPCC’s relevant guidelines. It also can simulate disturbances such as forest management operations, land-use change, wildfires, and insect outbreaks (see Kurz et al. (2009) for a detailed description). In a recent study, Moreau, Thiffault, Kurz, et al. (2023) assessed emissions and sequestration in different forest management strategies for Quebec, Canada using CBM-CFS3, from 2018 to 2050. They compared alternative scenarios to a business-as-usual strategy to evaluate emission reduction potential. The research highlights the importance of minimizing methane emissions from wood products at the end of their life cycle for optimizing mitigation outcomes in Quebec's forest sector. Despite not considering market competition and overlooking the techno-economic aspect, the study suggests potential opportunities for the sector to contribute to mitigation benefits through increased carbon sequestration, advancements in long-lived wood products, and optimal market substitution, with high uncertainties. This thesis uses the output of the model used in the study by Moreau, Thiffault, Kurz, et al. (2023) to examine various forest management strategies and their implications on biomass availability for bioenergy and forest net emissions within the energy system. To accomplish this, a thorough representation of Quebec's energy system is derived from NATEM in order to build a harmonized model with CBM-CFS3. CHAPTER 3 provides a detailed description of the integrated approach developed in this thesis.

1.4.3 Biogenic carbon in TIMES model

Nearly 70 countries (IEA-ETSAP, 2023) currently employ the TIMES model to optimize their energy systems or achieve their objectives of reducing greenhouse gas (GHG) emissions. As highlighted previously in section 1.4.1, overlooking biogenic emission flows may result in biased decision-making. Remarkably, none of the existing literature (section 1.2.3.2) has adopted an integrated approach that incorporates biogenic emission flows within the TIMES model.

1.5 Research objectives

The overarching objective of this research is to comprehensively analyze the potential contribution of the forest sector in facilitating decarbonization pathways. The achievement of the overarching objective of this thesis relies on addressing three specific unanswered questions, which serve as key objectives for this research:

- What is the contribution of forest-based bioenergy in achieving deep decarbonization in Quebec?
- Does the assumption of biogenic carbon neutrality affect decarbonization pathways?

- What is the role of biomass-based hydrogen in Quebec's energy transition compared to other emerging hydrogen technologies?

This thesis aims to provide valuable insights for policymakers and stakeholders involved in Quebec's energy transition by addressing these gaps in the existing literature and employing an integrated approach. The main contributions of this research are as follows:

This study develops a detailed modeling approach that considers various forest-based bioenergy pathways within a techno-economic framework to determine the contribution of forest-based bioenergy in achieving deep decarbonization in Quebec. These pathways are incorporated into the NATEM-Québec, a comprehensive bottom-up energy model. Furthermore, the analysis assesses the potential of forest-based bioenergy in Quebec under different greenhouse gas (GHG) emission reduction scenarios.

This research develops an integrated approach by combining CBM-CFS3, a stand- and landscape-level modeling framework, with NATEM to eliminate the carbon neutrality assumption in previous literature. The CBM-CFS3 provides outputs that help model different forest management strategies and their impacts on biomass availability for bioenergy, net forest carbon stocks, and emissions, to see if and how this biomass would be used within the energy system over the considered time horizon. Additionally, various forest-based bioenergy and BECCS pathways are modeled, and their associated GHG emissions and uptakes are integrated into NATEM-Quebec to evaluate potential decarbonization pathways by 2050. Notably, this marks the first instance of modeling biogenic CO_2 flows within an energy system model like TIMES.

Following the developed integrated approach, this research conducts a comprehensive regionalized techno-economic study focused on different hydrogen pathways, specifically in the Quebec province of Canada. The study accounts for GHG emissions and uptakes associated with forest management, BECCS, and biogenic CO_2 flows. By considering these factors, decision-makers can gain more accurate insights into the contribution of various emerging hydrogen technologies, including biomass-based hydrogen. It is crucial to avoid assuming carbon neutrality for forest biomass, as such assumptions can lead to accounting errors and biased decision-making.

CHAPTER 2

THE CONTRIBUTION OF FOREST-BASED BIOENERGY IN ACHIEVING DEEP DECARBONIZATION: INSIGHTS FOR QUEBEC (CANADA) USING A TIMES APPROACH

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Abstract

This study assesses the contribution of various forest-based bioenergy technologies when transitioning to a low carbon economy. A detailed modeling of different forest-based bioenergy pathways is provided following a techno-economic (bottom-up) approach. As an illustration, these pathways are implemented in NATEM-Québec, a detailed bottom-up energy model for Québec, Canada. It is the first time different primary and secondary forest-based bioenergy technologies are being modeled in such a detailed bottom-up energy system model like TIMES. A detailed analysis of forest-based bioenergy potential in Quebec is also provided under different greenhouse gas (GHG) emission reduction scenarios. Main insights are as follows. The transportation sector is the primary contributor to GHG emissions over the time horizon in all scenarios, except for the most stringent GHG reduction scenario (GHGB) in 2050. The industrial sector is the main emitter by 2050 in GHGB, indicating the difficulties to decarbonize heavy industry. Furthermore, an extensive electrification is required to reach the GHG reduction targets. The bioenergy share is expected to increase considerably in the transportation and industrial sectors, cutting down on the need to reduce GHG emissions.

Forest-based bioenergies such as cellulosic bioethanol, biobased heat, FT diesel and electricity as a co-product can effectively support this energy transition. The present study discerns forest-based bioenergies as an attainable decarbonization pathway for the province of Quebec and envisages a greater penetration of bioenergy than in the 2030 Plan for a Green Economy proposed by the government of Québec. Other world regions with a declining trend for traditional forest products should also consider such a strategy.

Keywords: GHG emissions; Forest-based bioenergy; TIMES model; Prospective analysis; Decarbonization pathways

2.1 Introduction

The forest industry sector has undergone remarkable changes in recent years as demand for traditional forest products has decreased across many countries such as the United States (US), Canada, and Nordic countries (Hurmekoski *et al.*, 2018 ; Jåstad *et al.*, 2019). For example, while the forest industry is an important economic sector for Canada, with a Gross Domestic Product (GDP) share of 1.3% and total revenues of $73.6 billion (FPAC, 2019), it is currently experiencing a decline due to an escalating global competition, a decrease in the US housing market and a sharp drop in the North American newsprint demand (Cambero et Sowlati, 2016). These countries are looking for new opportunities to compensate for the declining demand for traditional forest products (Hurmekoski *et al.*, 2018).

Declining trends in the forest industry market provide incentives to develop new products and processes. The climate change mitigation potential of forest products provides further incentives (Xu *et al.*, 2018). Forest-based bioenergy is one such product that has attracted attention, primarily because it usually has a lower carbon balance than its fossil counterparts. Unlike many renewables, biomass provides a storable energy solution and can be used within the existing fossil infrastructure. It facilitates the transition towards a renewable energy supply by enabling more intermittent renewable modes. Bioenergy also offers substantial benefits by enhancing energy supply security (cutting down the dependence on imported fossil fuels, diversifying supply patterns, and broadening the diversity of energy sources). It also accelerates the economic vitality of rural communities (Allen *et al.*, 2016). Petroleum products (e.g., diesel, gasoline) have a high energy density, uncomplicated storage and combustion properties that make them a perfect choice for powering transportation. Biofuels such as ethanol and biodiesel are renewable alternatives to gasoline and diesel, respectively. However, these biofuels are currently mainly produced from food crops, sugar, grain, and vegetable oils, threatening food security. There has thus been significant research on developing non-food-based biofuels, such as lignocellulosic biomass-based feedstocks that are abundant, low-priced and more sustainable than food crops (Van Walsum et Wheeler, 2013).

Many countries have announced ambitious plans to reduce their GHG emissions following national or international commitments such as the Paris Agreement (UNFCCC, 2015). For instance, Canada (Government of Canada, 2020), the European Union (European Commission, 2018), France, New Zealand, Spain, United Kingdom, are moving toward carbon neutrality by 2050, Sweden by 2045, Norway by 2030 (Welfle, Thornley et Röder, 2020), and China by 2060 (Vaughan, 2020). In such a context, bioenergy can have a substantial role in fossil-free energy systems (Jåstad *et al.*, 2020), especially forest-based bioenergy in North America and Nordic countries (with declining trend for traditional forest products). In Canada, for instance, bioenergy could be a key component of its climate change mitigation strategy (Langlois-Bertrand *et al.*, 2018). Likewise, the province of Québec (Canada), that is used as a case study, plans to achieve its objective to reduce its GHG emissions by 37.5% below 1990 by 2030 by various means such as an increase in bioenergy production by 50%, relative to 2013 (Government of Québec, 2020).

Indeed, when the forest is sustainably managed, the release of the biofuel carbon content during combustion can be compensated by the uptake of an equivalent amount of carbon from the atmosphere by growing forests. However, growing biomass demand may originate further land-use change emissions and a non-neutral biogenic carbon balance. Immediate combustion emissions might take several years to be sequestered through natural processes, which cause short-term warming effects even if the biogenic carbon balance is zero in the long-term (Berndes *et al.*, 2016). Furthermore, converting forest biomass into fuel, and then into useful energy, involves GHG emissions throughout the process as energy and material inputs are needed. The conversion efficiency affects the scale of GHG emission reductions, as more or less forest biomass must be converted to substitute a given amount of fossil energy (Allen *et al.*, 2016 ; Berndes *et al.*, 2016 ; Albers *et al.*, 2019).

Many studies have already assessed the role of bioenergy for climate change mitigation following different approaches. (Werner *et al.*, 2010) applied an integral model-based approach to examine the climate change mitigation potential of various forest management and wood use strategies. Temporal and spatial patterns of GHG emissions and sequestration have been analyzed in this study. On a global level, substitution of material for wood is recognized to be more effective than bioenergy generation. Nevertheless, in the regional context of Switzerland, bioenergy production showed advantage over material substitution. (Lemprière *et al.*, 2013) surveyed the biophysical mitigation potential of boreal forests. They indicated that avoiding GHG emissions and maintaining carbon stocks lead to the most considerable biophysical mitigation potential in the short-term. Nonetheless, exploiting forest-based biomass to accelerate carbon removal leads to higher emission mitigation potential on the long-term. (Smyth *et al.*, 2014) assessed the mitigation potential of Canadian managed forests from 2015 to 2050 using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). They considered seven forest management approaches and two harvested wood product strategies. Better utilization scenario (increasing utilization of harvested wood, maximizing salvage harvesting, avoiding burning residues, and collecting 50% of residues for bioenergy) showed the most climate change mitigation potential. (Lamers *et al.*, 2014) used CBM-CFS3 to analyze different scenarios for damaged forests of British Columbia. Using harvesting leftovers as bioenergy feedstock indicated a higher emission reduction potential than a protection reference scenario. (Wang *et al.*, 2015) developed an integrated dynamic, price-endogenous, partial equilibrium model of the forestry, agricultural, and transportation sectors to examine the GHG emission consequences of exporting pellets in the US. Pellets produced from the combination of agricultural and forest-based feedstocks showed better GHG mitigation opportunities than pellets made from just forest-based feedstock. (Smyth *et al.*, 2017) analyzed the climate change mitigation potential of local harvest residues for bioenergy in Canada using three models. The results suggested that the substitution of harvest residues for fossil fuels leads to GHG emission reduction. Whereas displacement of these residues for cleaner energy sources such as low-emission hydroelectricity resulted in further emissions. (Cintas *et al.*, 2017) employed a scenario-based approach to investigate the potential role of forest management in climate change mitigation in Sweden. According to this study, the Swedish forest sector contributes to achieving carbon neutrality by offering bioenergy and other forest products. Simultaneously, it acts as a carbon sink and maintains vegetation and soils. In a study by (Gustavsson *et al.*, 2017), the Heureka Regwise simulator and the Q-model were used to investigate the climatic implications of different forest management strategies, harvest residue extraction levels, and end-use options for forest products in Sweden. A scenario with high harvest and residue recovery rates was introduced as the most promising pathway toward climate change mitigation. But what are the most cost-effective pathways to reduce GHG emissions?

This study relies on NATEM (Vaillancourt *et al.*, 2017), a bottom-up energy system model, to overcome the limitation of the other approaches and take into account competition between the pathways on the market. Such models are considered relevant instruments to generate different scenarios, preparing deep insights for choosing a cost-effective or advantageous mix of technologies considering various assumptions and policy alternatives. The Integrated MARKAL-EFOM System (TIMES) (Loulou, Lehtilä, *et al.*, 2016) is a bottom-up partial-equilibrium model representing the entire energy system of a country or region over a long-term horizon. It typically includes extraction, transformation, distribution, end uses, and trade of various energy forms. Each step of the energy value chain is described by specific technologies represented with their techno-economic characteristics (e.g., cost and efficiency). The North American TIMES Energy Model (NATEM) belongs to the TIMES models family and is a highly detailed multi-regional optimization model of the Canadian energy sectors. It uses various and thorough parameters to optimize defined scenarios based on legislative policies, such as GHG emissions constraints.

Energy system models have been utilized to measure the bioenergy role in a few studies (Börjesson *et al.*, 2014), (Dodder *et al.*, 2015), (König, 2011), (Panos et Kannan, 2016), (Zhao *et al.*, 2015), and (Jåstad *et al.*, 2021). It is also the case for models relying on the TIMES approach. For example, Hugues et al., (Hugues, Assoumou et Maizi, 2016) have used the TIMES-FR model to investigate the French bioenergy sector penetration under GHG emission constraints. (Levasseur *et al.*, 2017) used NATEM in parallel with a life cycle assessment (LCA) method to investigate environmental impacts and market penetration of butanol production from pre-hydrolyzate in a Canadian Kraft dissolving pulp mill. (Albers *et al.*, 2019) coupled a TIMES model (TIMES-MIRET) with forest carbon modeling in the specific context of dynamic LCA (dynamic biogenic carbon models). They challenged the static approach toward combining LCA and partial-equilibrium model because climate change effects of biogenic carbon embedded in bioenergy are sensitive to time. Based on their results, a scenario considering dynamic biogenic carbon demonstrated more significant emission mitigation than a scenario without biogenic carbon. (Vaillancourt, Bahn et Levasseur, 2019) studied the potential penetration of bioenergy in Quebec by 2030 under different GHG emission reduction scenarios using NATEM-Quebec. However, this work focused on bioenergy in general (first- and second-generation biofuels), with only six lignocellulosic-based biofuels considered, and there was no detailed sensitivity analysis on biomass feedstock uses. In this paper, it is considered again that forest-based biofuels as non-edible feedstock are more socially acceptable to the Canadian public (Longstaff *et al.*, 2015).

A thorough search of the relevant literature yielded only a few papers that studied bioenergies in models covering energy and the economy. This manuscript aims to critically analyze factors affecting GHG emissions associated with forest-based bioenergy technologies by introducing them in NATEM-Quebec to investigate potential decarbonization pathways by 2050. It is the first time different primary and secondary forest-based bioenergy technologies are being modeled in such a detailed bottom-up energy model like TIMES. More precisely, the contributions of this paper are as follows. First, a detailed modeling of different forest-based bioenergy pathways is provided following a techno-economic (bottom-up) approach. Second, these pathways are implemented in a detailed bottom-up energy model for Québec (NATEM-Québec). This contributes to improving a state-of-art energy model used to provide consulting to different ministries in Quebec. Third, a detailed analysis of forest-based bioenergy potential in Quebec is provided under different GHG emission reduction scenarios. This contributes to the climate policy debate with a tool that includes a broad diversity of mitigation options that are necessary since the targets to be reached are ambitious. This study also performs a critical analysis of factors affecting GHG emissions associated with different forest-based bioenergies. Finally, this paper discusses how the insights gained in this study can be applied to other countries.

The remainder of the paper is organized as follows. Section 2 succinctly presents the TIMES modeling approach, the NATEM framework, forest-based resource supply, and associated conversion technologies. Section 3 presents detailed results, including energy and emission scenarios, GHG emissions analysis, forest-based feedstock, bioenergy role in final energy demand, and sensitivity analysis. Section 4 gives a complementary discussion. Section 5 contains a summary and conclusion.

2.2 Methodological approach

2.2.1 TIMES modeling approach

Models covering energy and the economy can be divided into two main categories. The first category takes a macroeconomic (top-down) approach to model the link between energy and the economy. The second employs a disaggregated (bottom-up) approach to model energy value chains while considering many substitutions and relative costs. Contrary to top-down models, bottom-up models are partial-equilibrium models and thus cannot provide a complete picture of the economy. But they are more suitable to describe systems with emerging energy sources such as biofuels or to describe explicit energy technologies (Bahn, 2018).

TIMES is such a bottom-up model that has been developed within the IEA ETSAP program. It provides potential configurations for the energy sector by comparing user-defined scenarios. The main outputs of a TIMES model include energy system configurations, energy flows, energy commodity prices, GHG emissions, capacities of energy technologies, energy costs and marginal emissions abatement costs. TIMES is cast as a linear programming (LP) problem. As such, it is comprised of decision variables, an objective function and constraints. Decision variables corresponds to choices to be made endogenously. The main types are related to energy technologies (installed capacities, new capacity additions, activity levels…) and energy commodities (quantities produced, stored, exported, imported…). The objective function corresponds to maximizing the total producer and consumer surplus. Under some simplifying assumptions (such as perfect competition on energy markets and a constant price elasticity for energy service demands), a single optimization yields an optimal configuration of the energy sector under user defined constraints. These constraints (referred to as the model's equations) express physical and logical relationships (e.g., production limits, energy balances…) that must be addressed to appropriately model the whole energy sector. The model also includes policy constraints such as GHG emission reduction targets that can be achieved through technology and fuel substitutions (Loulou, Goldstein, Kanudia, Lettila et Remme, 2016). TIMES complete documentation is publicly available (Loulou, Goldstein, Kanudia, Lettila et Uwe Remme, 2016), including a comprehensive explanation of the sets, attributes, variables, and equations of the model. TIMES scope includes local, national, multi-regional, or global energy systems over a multi-period time horizon. A typical time horizon is the year 2050. Short periods (1 to 2 years) are specified in early stages, while longer periods (5 to 15 years) are used in subsequent periods due to increasing uncertainty in data. Besides, there are time divisions within each year. These time slices correspond to different seasons and intraday periods (e.g., day, night, peak hours…) (Vaillancourt *et al.*, 2017).

2.2.2 NATEM model

In this paper, the North American TIMES Energy Model (NATEM) is used to perform energy policy analyses for the Quebec Province of Canada. Following a TIMES approach, NATEM represents the Reference Energy System (RES) of all Canadian jurisdictions, including 70 end-use demands for energy services in different sectors (agriculture, commercial, industrial, residential, and transportation), see (Vaillancourt *et al.*, 2017). From NATEM, a detailed representation of the Quebec's energy system has been extracted, thereafter called NATEM-Quebec, to assess forest-based bioenergy technologies in the context of a region endowed with forest-based biomass. The spatial scale of NATEM-Quebec concerns the whole province, with data disaggregated by sub-regions. The temporal horizon is 2011-2050 with 9 periods and 16 annual time slices. All costs are presented in 2011 Canadian dollars (CAD) and a global annual discount rate of 5% is used (Vaillancourt, Bahn et Levasseur, 2019). The large database of NATEM-Quebec (with, e.g., its more than 4,000 explicit energy technologies) is managed using the VEDA2.0 model management system (KanORS-EMR, 2023), whereas TIMES is coded in the GAMS modeling language and the resulting large LP problem (more than 300,000 equations and close to 400,000 variables) is solved to optimality using the CPLEX solver (GAMS, 2023).

2.2.3 Forest-based biomass

2.2.3.1 Resource supply

Instead of a simple category labeled “forest residues” as the only forest-based feedstock in NATEM (Vaillancourt, Bahn et Levasseur, 2019), different forest-based biomass sources have been introduced along with new technologies that need specific feedstock types. As a numerical illustration of our approach, the availability of forest-based feedstocks in the province of Quebec by 2050 are given in Table 2.1. Forest-based feedstocks are characterized according to their physical properties, related activity, and final usage (Allen *et al.*, 2016). Forest industry residues include sawdust and shavings mainly from sawmills and oriented strand board (OSB) mills. Also mill residue surplus is considered as an untapped forest industry residue source. Hog fuels consist of bark-contained or coarse wood refuse generated in sawmill and plywood-veneer. Also, unutilized hog fuel is considered as an untapped hog fuel source. Wood chips originate from sawmills and plywood-veneer. Firewood originates from forests or farms through splitting wood logs by saw-splitters. Pulp and paper waste are mainly solid waste generated in pulp and paper plants. Spent liquor is a by-product of paper production during the kraft process. Slash (forest leftovers) generates from forestry activities, including branches, needles, leaves, trunks and treetops (Ghafghazi *et al.*, 2017 ; Hydro Québec, 2015 ; Bajpai, 2015 ; Speight, 2019).

Table 2.1 Forest-based feedstock's availability, price, and energy coefficient in Quebec

Type	**Source**	**Energy coefficient**[1]	**Total estimated**[2]		**Price**[3]	**First yearly potential**[4]	**Extra feedstock price**[5]	**Second yearly potential**[6]	**Extra feedstock price**[7]
		[MJ/kg]	[ton/yr]	[PJ/yr]	[$/GJ]	[PJ/yr]	[$/GJ]	[PJ/yr]	[$/GJ]
Forest industry residues	Sawmill/OSB/ untapped	18.89	1,550,332	29.3	5.51	8.8	8.3	13.2	16.5
Hog fuel	Sawmill/plywood veneer/untapped	18.30	1,281,163	23.4	5.51	7.0	8.3	10.6	16.5
Chips	Sawmill/plywood veneer	18.89	4,076,782	77.0	7.77	23.1	11.7	34.7	23.3
Firewood	Forest/farms	18.76	2,771,850	52.0	12.35	15.6	18.5	23.4	37.1
Slash	Forest	18.95	4,430,000	83.9	4.41	25.2	6.6	37.8	13.2
Pulp and paper waste	Pulp and paper plant	17.08	915,172	15.6	5.51	4.7	8.3	7.0	16.5

Spent liquor	Kraft process	12.29	3,018,750	37.1	4.41	11.1	6.6	16.7	13.2

[1] (Hydro Québec, 2015 ; Carrasco *et al.*, 2017)

[2] (Ghafghazi *et al.*, 2017 ; Hydro Québec, 2015)

[3] (Hydro Québec, 2015 ; Carrasco *et al.*, 2017 ; Natrural Resources Canada, 2020)

[4] assumed to be 30% of the total estimated

[5] assumed to be 1.5 times higher than the estimated price

[6] assumed to be 45% of the total estimated

[7] assumed to be 3 times higher than the estimated price

For each of these feedstocks, a supply curve has been defined in NATEM-Quebec with different availability potentials and their relative costs. Extra feedstocks are assumed available at a higher price. Accordingly, two different yearly potentials for forest-based feedstocks are investigated in this study. The first yearly potential could be seen as providing extra biomass within the province. The second annual potential might be viewed as supplying feedstock from other regions.

2.2.3.2 Bioenergies and conversion technologies

Figure 2.1 presents the reference energy system of common and emerging conversion technologies to produce lignocellulosic-based bioenergy. It displays the flow of resource supply, production and conversion technologies to end-use technologies. Table 2.2 and Table 2.3 present an overview of these technologies that have been added to NATEM. The data for 45 primary and secondary forest-based bioenergy technologies were acquired from various literature and modeled in NATEM after required modifications. Mainly studies that calculated the process's costs using a classical process design approach (Peters, Timmerhaus et West, 2003) were selected for this work. The primary modifications are as follows: associated feedstocks were defined for each of the processes; energy inputs required during conversion processes were calculated; energy efficiency and investment cost were revised and quantified;

fixed and variable operating costs recalculated by excluding energy costs since they are already considered by NATEM; all the mentioned costs were divided by the installed capacity which is the total amount of energy produced. A more detailed description is given in APPENDIX I (Part A). With these conversion technologies, biomass is transformed into three primary outputs: electricity and heat as two energy outputs, and chemical feedstock as a non-energy output. Conversion technologies are divided into two main groups: thermo-chemical and biochemical/biological. In addition, mechanical conversion process is considered a primitive conversion technology to transform biomass into energy (McKendry, 2002).

Mechanical conversion processes of forest-based biomass mainly include splitting, chipping, pressing, and grinding that produce solid fuels such as logs, densified wood logs, wood pellets, wood chips, and wood powder (Douard, 2010 ; McKendry, 2002). However, pelletizing is only considered due to a lack of data for other types of mechanical conversion processes. Thermochemical conversion processes are divided into four main categories: combustion, gasification, pyrolysis, and hydrothermal liquefaction (Pang, 2019). Besides, charcoal production and roasting (Douard, 2010) are also considered as thermochemical conversion technologies that produce charcoal, briquette, and roasted wood. Biochemical processes include fermentation and anaerobic digestion (Pang, 2019). Different types of fermentation conversion processes have been investigated in this study. Hybrid conversion processes integrate thermochemical and biochemical conversion processes (Van Walsum et Wheeler, 2013). A description of biofuel conversion pathways is available in APPENDIX I (Part B).

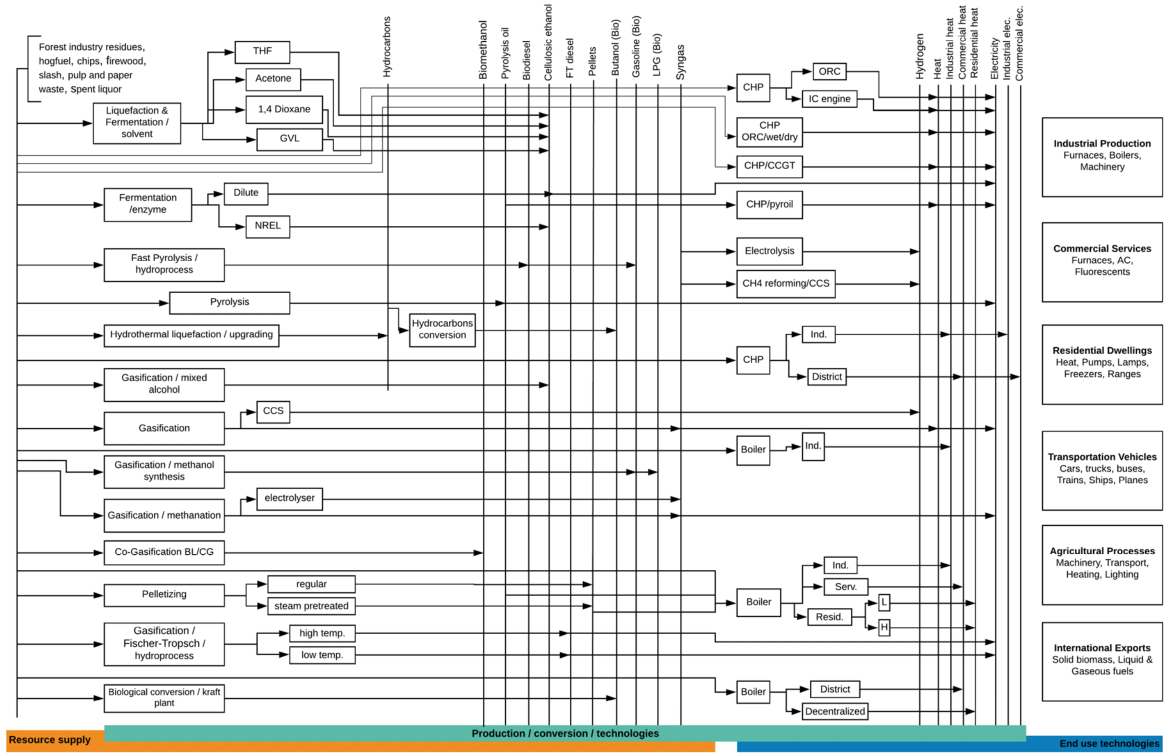

Figure 2.1 Detailed forest-based bioenergy conversion processes in NATEM-Quebec

Table 2.2 Primary conversion processes

Technology	**Conversion process**	**Bioenergy**	**Reference**
Biomass HTL. Upgrading system 69.9 MGGEPY	Hydrothermal liquefaction	Hydrocarbons	(Zhu *et al.*, 2014)
Co-Gasification. Methanol grade AA. Black liquor. Crude glycerol	Co-Gasification	Biomethanol	(Carvalho *et al.*, 2018)
Fast pyrolysis and hydroprocessing 35 MGPY	Fast pyrolysis	Gasoline(bio), Biodiesel	(Li *et al.*, 2017 ; Wright et Brown, 2019)
Fermentation. Butanol Production	Fermentation	Butanol(bio), Heat	(Levasseur *et al.*, 2017)
Fermentation. Ethanol. Enzyme. Dilute-acid 53.4MGPY	Fermentation	Cellulosic bioethanol, Electricity	(Li *et al.*, 2018 ; Kazi *et al.*, 2010)

Fermentation. Ethanol. Enzyme. NREL 61MGPY	Fermentation	Cellulosic bioethanol	(Li *et al.*, 2018 ; Humbird *et al.*, 2011)
Fischer-Tropsch. Catalytic. Hydroprocessing. High temperature. Flow gasifier 41.7MGPY	Gasification/Fischer-Tropsch	FT diesel, Electricity	(Swanson *et al.*, 2010)
Fischer-Tropsch. Catalytic. Hydroprocessing. Low temperature. Fluidized bed gasifie 32.3MGPY	Gasification/Fischer-Tropsch	FT diesel, Electricity	
Gasification facility. Gasifier + methanation. Wood	Gasification/methanation	Syngas, Electricity	(Panos et Kannan, 2016)
Gasification facility. Gasifier + methanation. Wood. Electrolyser	Gasification/methanation	Syngas	
Gasification.Wood.20MW	Gasification	Syngas, Electricity, Heat	(Moret *et al.*, 2017)
Gasification to ethanol 61.8 MMGPY/mixed alcohol 76.2 MMGPY	Gasification/mixed alcohol	Cellulosic bioethanol	(Phillips *et al.*, 2007 ; Wright et Brown, 2019)
Gasification. Bio. CCS. Hydrogen	Gasification/Hydrogen	Hydrogen	(Moret *et al.*, 2017 ; Tock, 2013)
Gasification. Methanol synthesis, Methanol to Gasoline (MTG) 49.6 MGPY	Gasification/methanol synthesis	Gasoline(bio), LPG (bio)	(Phillips *et al.*, 2011)
Liquefaction. Fermentation. Ethanol. Solvent. 1,4-Dioxane 39.4MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	(Li *et al.*, 2018)
Liquefaction. Fermentation. Ethanol. Solvent. Acetone 34.8MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	
Liquefaction. Fermentation. Ethanol. Solvent. GVL 50.6MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	(Li *et al.*, 2018 ; Han *et al.*, 2015)
Liquefaction. Fermentation. Ethanol. Solvent. THF 53.3MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	(Li *et al.*, 2018)
Pellet. Production. Forest residue. Regular 190kt	Pelletizing	Pellets	(Shahrukh *et al.*, 2016)
Pellet. Production. Forest residue. Steam pretreated 290kt	Pelletizing	Pellets	
Pyrolysis. Wood 10MW	Pyrolysis	Pyrolysis oil	(Moret *et al.*, 2017)

Continued

Table 2.2 Continued.

Technology	**Conversion process**	**Bioenergy**	**Reference**
CHP ORC system. Wet/dry wood 2.08MWe	CHP/ORC/Wet/dry	Electricity, Heat	(Moret *et al.*, 2016)
CHP. biomass combustion. ORC 2.5MW	CHP/ORC	Electricity, Heat	

CHP. biomass gasification. IC engine 3MW	CHP/Gasification/IC engine	Electricity, Heat	(Rentizelas *et al.*, 2009)
CHP. District. Wood 20MWth	CHP/District	Heat, Electricity	(Moret *et al.*, 2017)
CHP. Industry. Wood 20MWth	CHP/Industry	Heat, Electricity	
Boiler. Decentralized. Wood. 0.1MW	Boiler/Decentralized	Heat	
Boiler. District. Wood.10MW	Boiler/District	Heat	
Boiler. Industry. Wood.10MW	Boiler/Industry	Heat	
Boilers. Industrial. Wood	Boilers/Industrial	Heat	(Panos et Kannan, 2016)
Boilers. Residential. Wood. High	Boilers/Residential	Heat	
Boilers. Residential. Wood. Low	Boilers/Residential	Heat	
Boilers. Services. Wood	Boilers/Services	Heat	

Table 2.3 Secondary conversion processes

Technology	**Conversion process**	**Bioenergy**	**Reference**
CH4 reforming. CCS. Hydrogen	CH4 reforming/Hydrogen	Hydrogen	(Moret *et al.*, 2017 ; Tock, 2013)
Electrolysis. Hydrogen	Electrolysis/Hydrogen	Hydrogen	(Moret *et al.*, 2017 ; Gassner et Maréchal, 2008)
CHP. Combined-Cycle Gas Turbine CCGT. SNG 34-55MWe	CHP/CCGT	Electricity, Heat	(Moret *et al.*, 2016)
CHP. Oil/Bio-Oil 0.2-2MWe	CHP/Bio-Oil	Electricity, Heat	
Boilers. Industrial. Oil	Boilers/Industrial	Heat	(Panos et Kannan, 2016)
Boilers. Industrial. Pellet	Boilers/Industrial	Heat	
Boilers. Residential. Oil. High	Boilers/Residential	Heat	
Boilers. Residential. Oil. Low	Boilers/Residential	Heat	
Boilers. Residential. Pellet. High	Boilers/Residential	Heat	
Boilers. Residential. Pellet. Low	Boilers/Residential	Heat	
Boilers. Services. Oil	Boilers/Services	Heat	
Boilers. Services. Pellet	Boilers/Services	Heat	

2.2.4 Energy and emission scenarios

Four scenarios (Table 2.4) are considered to explore the potential contribution of emerging forest-based bioenergy in Quebec’s energy transition: i) a business-as-usual (BAU) scenario without any additional GHG emission reduction constraints beyond existing governmental policies, and without lignocellulosic-based bioenergies; ii) a business-as-usual scenario in which the model can use the lignocellulosic-based bioenergies (BAU+BIOF) to explore the role of these bioenergies in Quebec's energy system in the absence of additional GHG emission reduction constraints; and iii) two reduction scenarios with different GHG emission targets to be reached by 2050. In all scenarios, demands for energy services are projected through 2050 from 2011 by means of a set of comprehensible socio-economic assumptions (GDP, GDP per capita, population growth) from the Trottier Energy Futures Project (TEFP, 2016). And again, all these scenarios consider existing governmental energy and climate policies (Government of Canada, 2010 ; Government of Quebec, 2012 ; Ministère des Transports du Québec, 2015 ; NHTSA, 2011).

Table 2.4 Considered scenarios

Scenario	**GHG constraints**	**Forest-based bioenergy technologies**
BAU	No additional GHG emission reduction constraints beyond existing governmental policies	No
BAU+BIOF	Same as BAU	Yes
GHGA	BAU with GHG emission reduction targets of 30% by 2030 and 70% by 2050 (from 1990 level)	Yes
GHGB	BAU with GHG emissions reduction targets of 37.5% by 2030 and 80% by 2050 (from 1990 level)	Yes

NATEM considers most of the GHG emissions caused by fuel combustion and fugitive sources from the energy sector, which were responsible for 66% of Canadian emissions in 1990 (58.6 Mt CO_2-eq) and 69% in 2013 (56.3 Mt CO_2-eq). Emission reduction constraints are imposed at the different periods using a linear interpolation based on target years (2030, 2050).

2.3 Result analysis

2.3.1 GHG emissions

In the BAU scenario, GHG emissions decrease by 4.1% between 2011 and 2025, before increasing by 25.9% between 2025 and 2050 (Figure 2.2). The first decreasing trend is due in particular to the substitution of some fossil fuel vehicles by electric vehicles due to governmental policies included in the scenario. However, growing energy service demands cause GHG emissions to increase again afterwards. The BAU+BIOF scenario shows slightly higher GHG emissions than the BAU scenario because of a switching to cellulosic bioethanol (mainly because of cheaper feedstock), which has a higher emission coefficient than bioethanol from agriculture-based feedstock. To achieve the imposed GHG reduction targets, compared to the baseline (BAU), emissions are reduced by 22.5% (GHGA), respectively 30.8% (GHGB) in 2030, and by 66.8% (GHGA), respectively 77.9% (GHGB) in 2050.

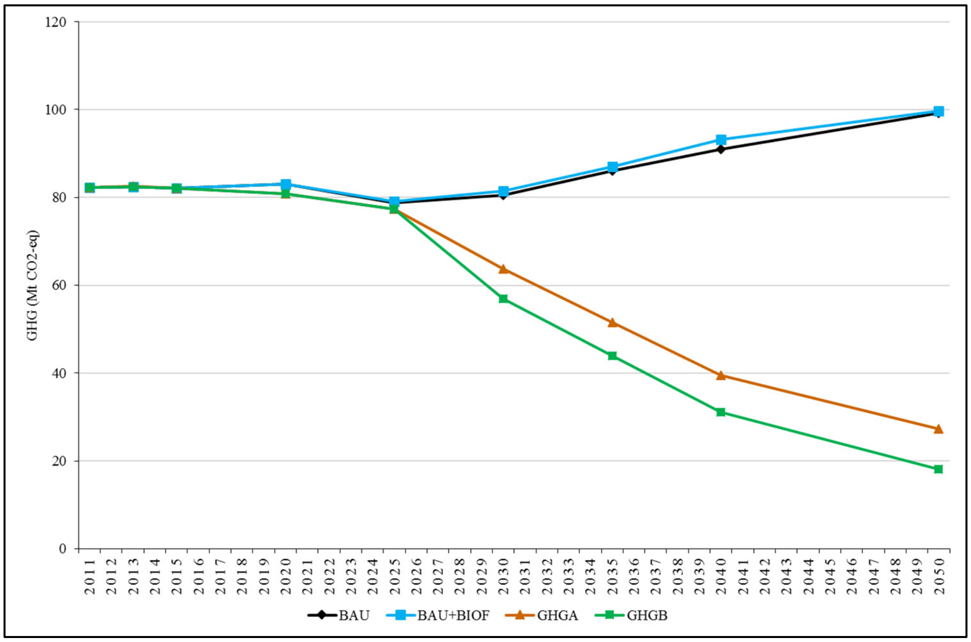

Figure 2.2 Total GHG emissions in Quebec

Figure 2.3 displays energy related GHG emissions by sector (agriculture, commercial, electricity, industrial, residential, production, and transportation). Transportation is responsible for more than half of total GHG emissions in the different time periods and scenarios, except for BAU+BIOF (49.5%) in 2030 and GHGB (21%) in 2050. Dependence upon fossil fuels to satisfy transportation demands is the main reason for this sector's emissions. Emissions for the industrial sector in the BAU and BAU+BIOF scenarios increase by around 54% and 59% respectively in 2050, compared to 2011. Besides, emissions for the production sector increase by 28.6% and 17.5% in the BAU and BAU+BIOF sectors, respectively. The production sector includes primary energy supply.

In the GHGA scenario, significant reductions are achieved in the transportation, industrial, commercial, and residential sectors of 24.2, 6.7, 4.9, and 3.2 $MtCO_2$-eq in 2050, respectively, compared to baseline values. In the GHGB scenario, further reductions are necessary in the transportation and industrial sectors to reach the more stringent target. The transportation, industrial, commercial, and residential sectors present 30.6, 7.1, 4.9, and 3.3 $MtCO_2$-eq of emission abatements in this scenario in 2050, respectively, compared to baseline values. In GHGB, the industrial sector is the main emitter by 2050, highlighting the challenge to decarbonize heavy industry.

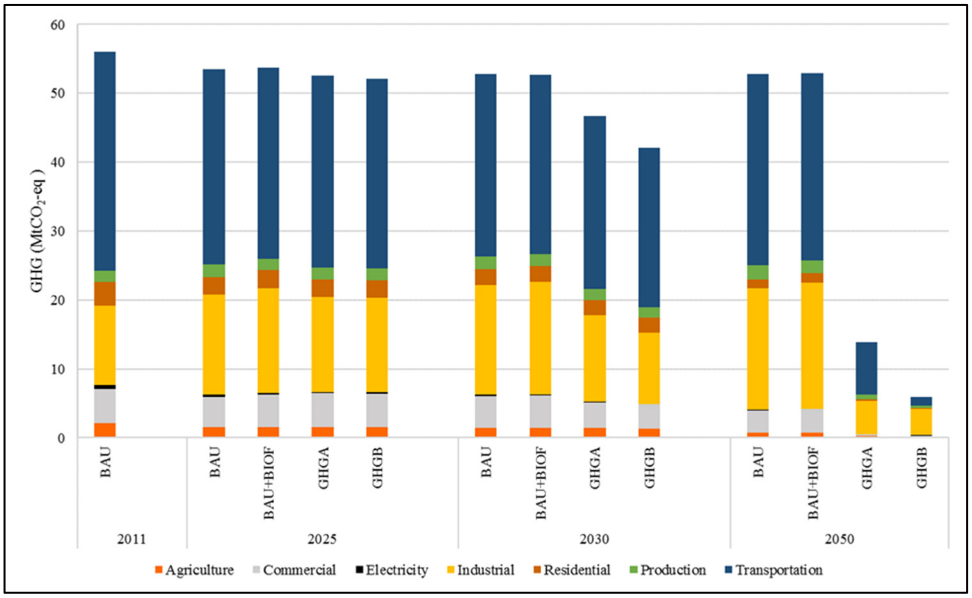

Figure 2.3 Energy-related GHG emissions by sector in Quebec

2.3.2 Primary energy production

Primary energy production (PEP) highly relies on hydroelectricity and biomass in Quebec (Figure 2.4). Renewable consists of other types of renewable energies such as solar and wind. Other energy sources such as coal, gas, and oil are being imported to Quebec. A twofold increase in the share of biomass in PEP is expected in the GHG reduction scenarios relative to BAU in 2050.

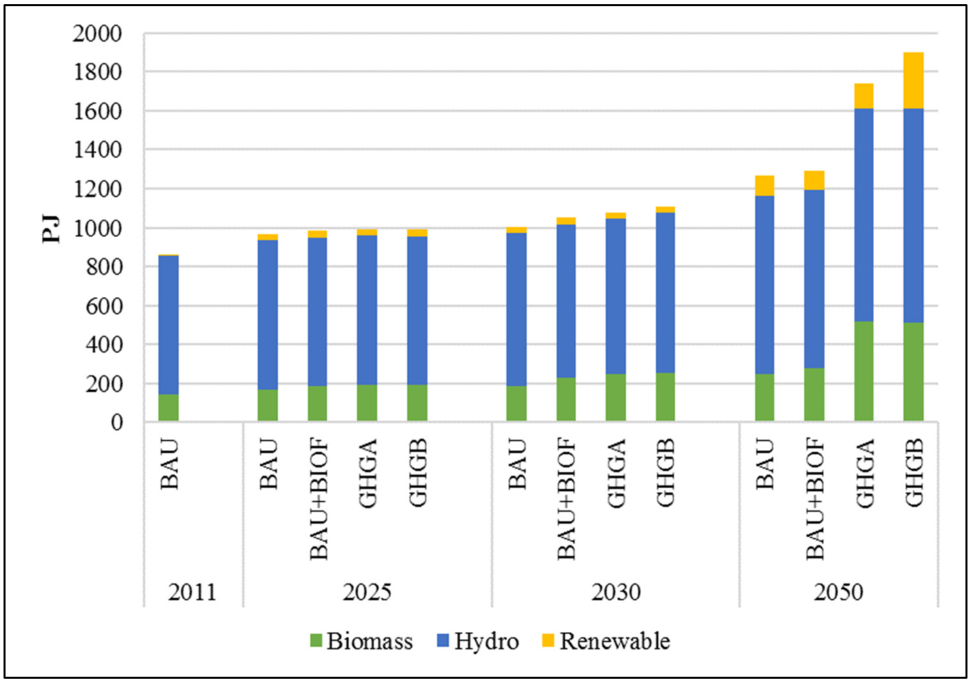

Figure 2.4 Primary energy production in Quebec

2.3.3 Forest-based residues as feedstock

Figure 2.5 presents the consumption of biomass as an energy source. Forest-based biomass (forest industry residues, hog fuel, chips, firewood, slash, spent liquor, pulp and paper waste) is more in demand than other types of biomass, mainly because of its lower price. Other biomass types consist of agriculture residues, canola, corn, soybeans, dedicated crops, greasy residues, and municipal wastes. The share of these other biomass sources is 6% and 29% of the total biomass demand in the BAU scenario in 2011 and 2050, respectively. In the BAU+BIOF scenario, the amount of forest-based biomass is 208.4 PJ in 2050, 30.9 PJ more than in the BAU scenario. The biomass share escalates considerably to help meet energy service demands with a low emission profile in the GHG emission reduction scenarios. The amount of other biomass sources decreases by 4.3 PJ in the GHGB scenario compared to the

GHGA scenario. The amount of forest-based biomass is the same for both reduction scenarios because of the feedstock's competitive price and limited forest-based biomass.

Forest slash is the primary feedstock in all the scenarios because of its lower price. Municipal wastes are another primary feedstock after the year 2025, because of emerging technologies which can use municipal wastes as feedstock. In the GHG emission reduction scenarios, the mix of feedstock is more diversified. Wood chips, firewood, hog fuel, and spent liquor are in high demand mainly because of the limited availability of slash, municipal waste or any other cheaper feedstock.

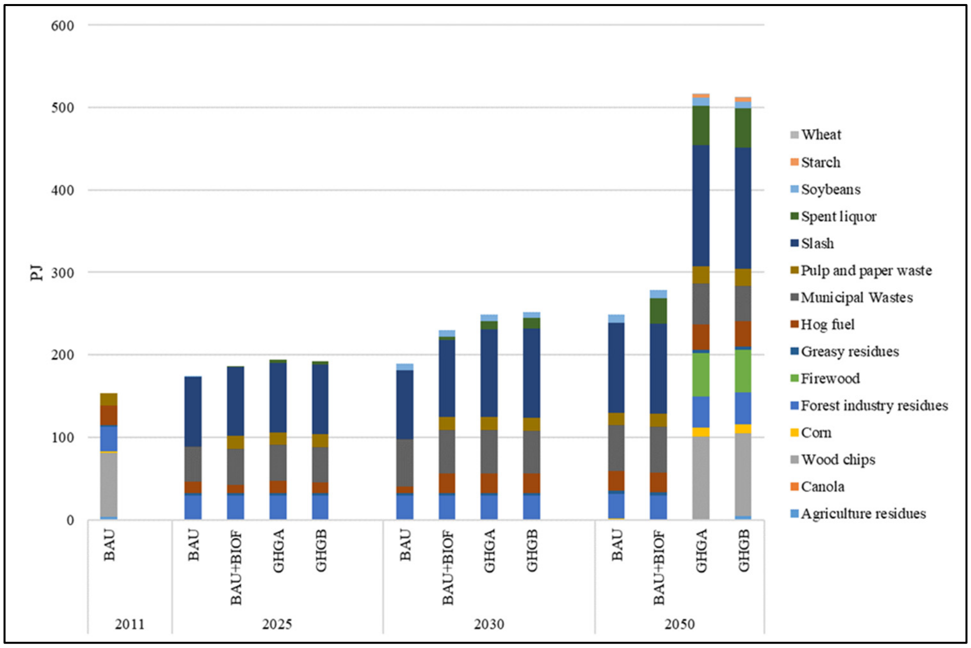

Figure 2.5 Consumption of feedstock by type for bioenergy production in Quebec

In the BAU scenario, the maximum amounts of forest industry residues, hog fuel, pulp and paper waste available at minimum cost as well as the first and second yearly potential of slash are utilized to meet the feedstock demand for cellulosic bioethanol, pellet, electricity, and heat for industry and residential sectors in 2050. With the addition of emerging technologies (BAU+BIOF), all the feedstock consumed in the BAU scenario except corn and 83% of spent liquor available at minimum cost are used. Even though the same types of bioenergy are produced in the BAU+BIOF scenario, more of them are forest-based. Corn is not used as a feedstock to produce ethanol. Instead, forest slash is used to produce cellulosic ethanol and spent liquor to produce heat.

All the forest-based feedstock available at minimum cost, first yearly potential (except for firewood), and all the slash accessible in the second yearly potential are consumed in both GHG reduction scenarios in 2050 (see again Table 2.1). The same type of bioenergy, but in higher quantities, are produced in GHG reduction scenarios. FT diesel is the only new bioenergy that is produced in GHG reduction scenarios in 2050.

2.3.4 Final energy consumption

Figure 2.6 displays the final energy consumption. In 2011, it was dominated by oil products, electricity, and heat. In the baseline scenarios, energy consumption moderately increases between 2011 and 2030, while it intensifies in 2050 relative to 2011. The share of oil products gradually decreases, and the share of electricity, heat, and natural gas increases in consecutive years. Significant changes occur in GHG reduction scenarios by 2050. The percentage of electricity and heat are 60% and 70% of final energy consumption in the GHGA and GHGB scenarios, respectively, in 2050. This indicates that extensive electrification is required to reach the GHG reduction targets. The contribution of bioenergy increases significantly (20% and 17% of final energy consumption in the GHGA and GHGB scenarios, respectively, in 2050).

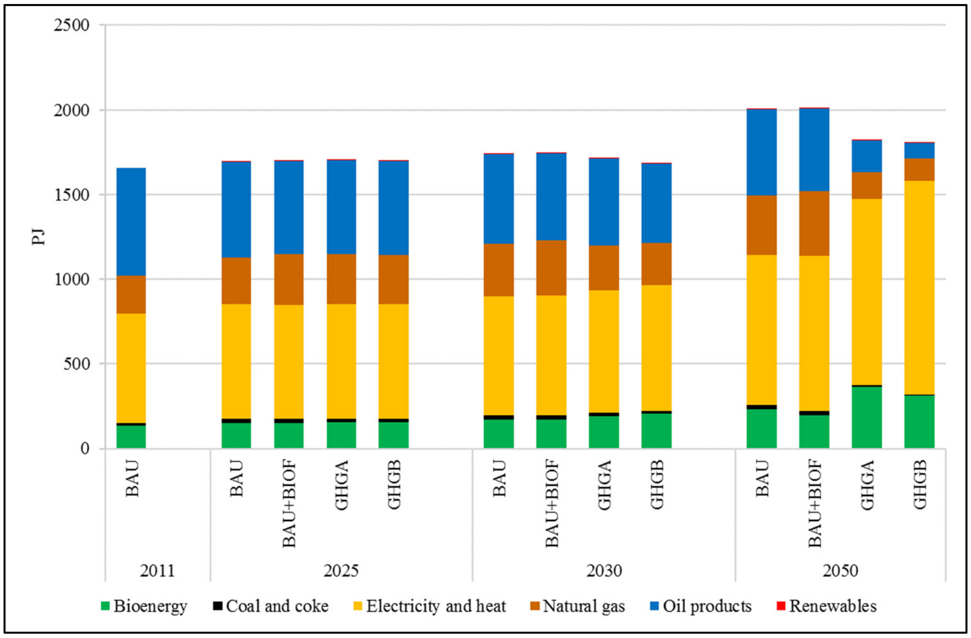

Figure 2.6 Final energy consumption in Quebec

2.3.5 The contribution of bioenergy in final energy consumption

Bioenergy use increases over the time horizon in BAU and BAU+BIOF scenarios (Figure 2.7). This trend is boosted by strict GHG emission reduction constraints in GHGA and GHGB scenarios. Bioenergy consumption in the GHGA and GHGB scenarios increases by 73% and 112% respectively in 2030, and by 203% and 164% respectively in 2050, relative to 2011. The total amount of bioenergy in the GHGB scenario is lower than in the GHGA scenario, as priority is given to use limited feedstocks for some bioenergy such as cellulosic bioethanol instead of bio-based heat.

Biodiesel and bioethanol are the only bioenergies consumed in 2011. Afterwards, there is a more diverse consumption of bioenergy types. The industrial sector is the main consuming sector, except in GHG reduction scenarios by 2050, in which transportation is the primary consumer. Bioenergy consumption in the industrial sector decreases by about 2.6% in the BAU scenario and 16.4% in the BAU+BIOF scenario in 2030 compared to 2011. Expected demand reduction for pulp and paper in this period is the main reason for this fall-off. However, the industrial sector's bioenergy consumption is increased afterwards following growing end-use demands. In the GHG reduction scenarios, consumption of bioenergy in the industrial sector continues to grow relative to the BAU scenario. The amount of industrial bioenergy usage in the GHGB scenario is 35% of the bioenergy in the GHGA scenario in 2050, stemming from the growing demand for bioenergy in the transportation sector to satisfy GHG constraints. In general, bioenergy is used for space heating in the residential sector, mainly from solid biomass. However, it is diversified in GHG scenarios through the use of biodiesel and FT diesel. Bioenergy consumption in this sector decreases over time in all scenarios. By introducing new technologies, solid biomass, biodiesel, and FT diesel are consumed to provide space heating and liquid fuel in GHG scenarios for commercial and agriculture sectors.

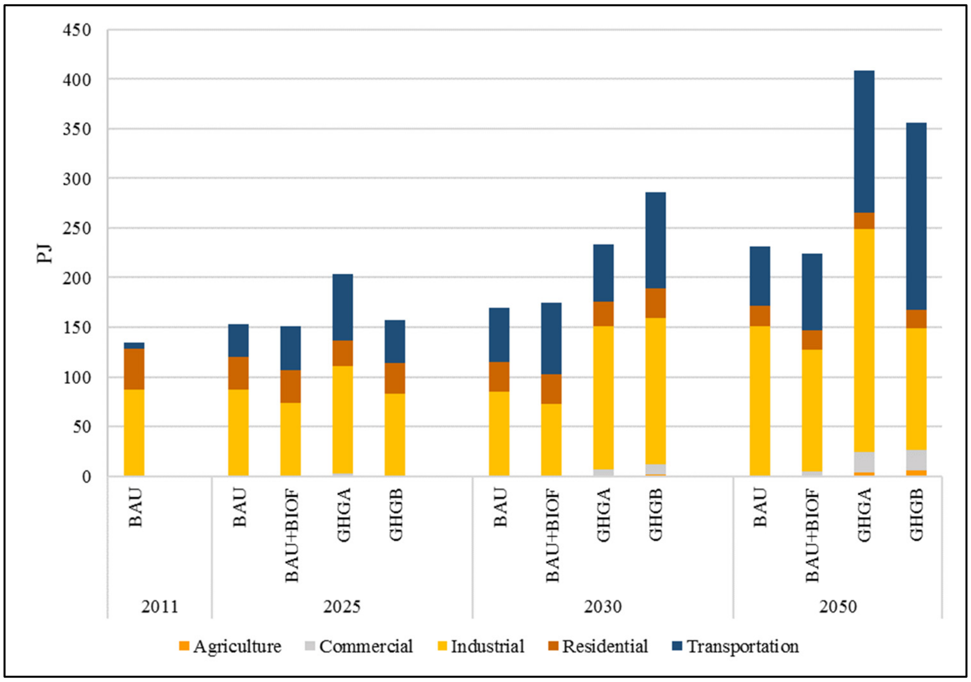

Figure 2.7 Consumption of bioenergy by end-use sector in Quebec

Figure 2.8 presents the consumption of the different types of bioenergy. Bio-based heat and electricity accounts from 90% (2011) to 64% (2030) in the BAU scenario. This reduction is due to limited feedstock and emerging new sources of bioenergies like biodiesel, bioethanol, FT diesel, bio methanol, and biomethane. The bioenergy consumption increases by around

36% in the BAU and 29% in the BAU+BIOF scenarios to meet the demand in 2050 compared to 2030. By introducing diversified forest-based feedstock in NATEM and defining new conversion technologies, cellulosic bioethanol becomes more available than first generation bioethanol. It reaches the highest amount of 111 PJ in the GHGB scenario in 2050.

The use of diverse bioenergy continues in the GHG reduction scenarios, where the highest use of bioenergy is reached. Biodiesel, bio methanol, and bio-based heat consumption reduces in the GHGB scenario in 2050 compared to the BAU scenario in 2050, mainly due to the diversion of feedstock for the production of cellulosic bioethanol.

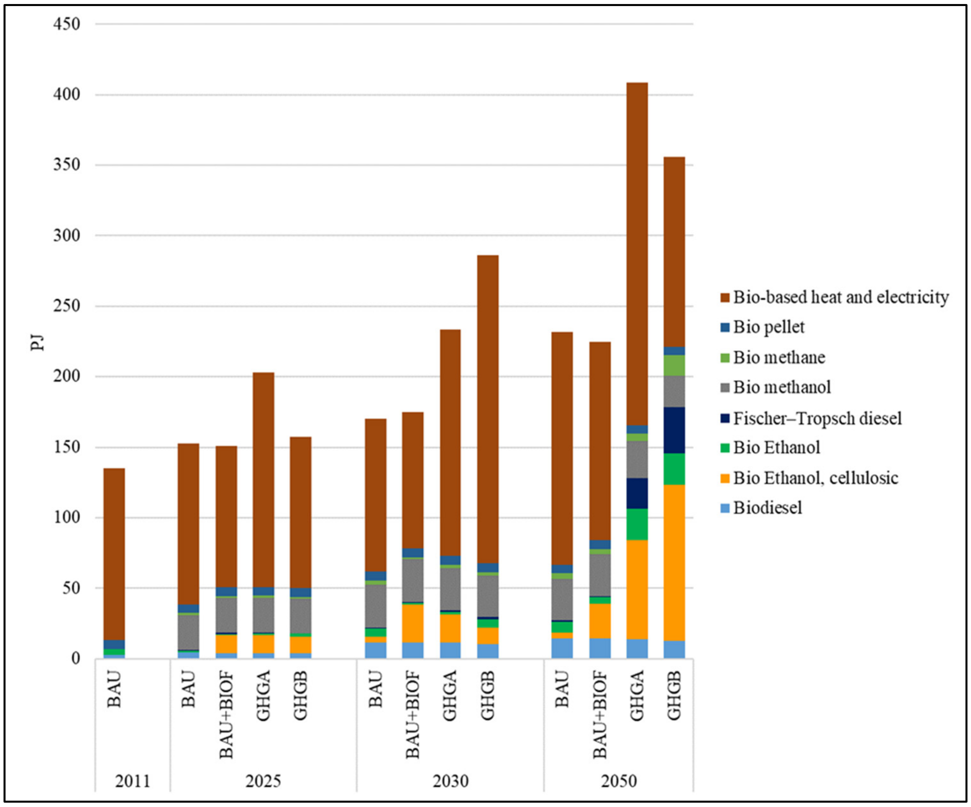

Figure 2.8 Consumption of bioenergy by type in Quebec

Bioenergy production from forest-based technologies is displayed in Figure 2.9. Besides, biomass consumption by these technologies is given in Table 2.5. Cellulosic bioethanol is the primary bioenergy produced in BAU+BIOF, reaching 26 PJ and 24 PJ in 2030 and 2050, respectively. Besides, the amount of bio-heat production grows from 1 PJ to 28 PJ in this scenario over the time horizon. Production of industrial heat in the GHG reduction scenarios increases from 3.7 PJ in 2025 to more than 23 PJ in 2050. Similarly, district heat increases from 2.9 PJ in 2030 to more than 19 PJ in 2050. The model uses 19.5 PJ and 12 PJ of cellulosic bioethanol for the GHGA and GHGB scenarios in 2030, respectively. However, these amounts increase by almost 2 and 8 times in 2050 compared to 2030, respectively. Bioenergy production is more diversified in GHG reduction scenarios by producing FT diesel and electricity as a co-product in the GHGB in 2030. The amount of FT diesel increases in the following years for GHG reduction scenarios and reached 21 PJ and 32 PJ in 2050 for the GHGA and GHGB, respectively.

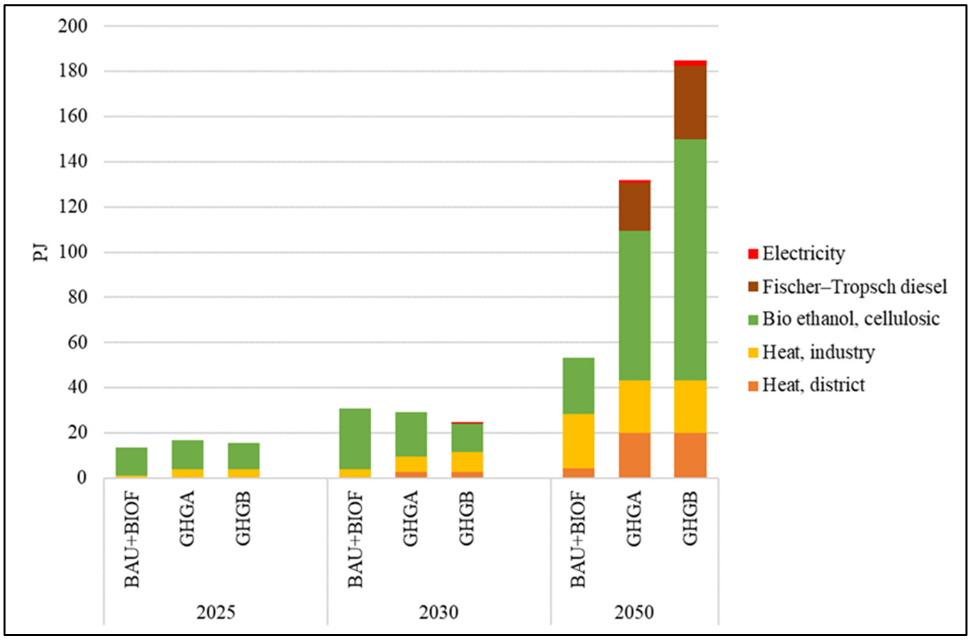

Figure 2.9 Bioenergy production from forest-based technologies in Quebec

Forest slash and spent liquor are the primary feedstock to produce bioenergy from forest-based technologies (Table 2.5). However, feedstock consumption becomes more diversified in GHG reduction scenarios to meet biomass demand. Gasification to cellulosic bioethanol conversion technology demonstrates that forest-based feedstock could be converted to bioethanol in a cost-competitive way. NATEM relies on this technology to consume forest slash in the BAU+BIOF and GHG reduction scenarios in 2025. This technology produces more biofuel in the following milestone years than in 2025 by consuming other biomass types in all three scenarios. As a result, cellulosic bioethanol production increases and reaches its maximum amount in the GHGB scenario (107 PJ; see Figure 2.9).

The model switches to Fischer-Tropsch catalytic conversion technology to provide required FT diesel for agriculture, commercial, industrial, residential, and transportation sectors in the GHGA (by 2050) and GHGB (by 2030) scenarios. As in (Swanson *et al.*, 2010), the model relies on FT catalytic conversion technology with high-temperature gasification instead of low-temperature gasification because of higher fuel yield. Furthermore, industrial and district boilers are used over time in all scenarios to meet heat requirements in the mentioned sectors. The rest of the modeled forest-based technologies are not part of the solution mainly because of a high marginal investment cost or a high emission factor for their bioenergy consumption.

Table 2.5 Forest-based biomass consumption by specific technologies

Technology	**Scenario**	**BAU+BIOF**	**GHGA**	**GHGB**	**BAU+BIOF**	**GHGA**	**GHGB**	**BAU+BIOF**	**GHGA**	**GHGB**	**Bioenergy**
	Feedstock /Year	**2025**			**2030**			**2050**			
Boiler. district. wood. 10MW	Spent liquor	0.01	0.01	0.01	0.01	3.36	3.36	5.10	23.0	23.1	Heat, district
Boiler. industry. wood. 10MW	Spent liquor	1.07	4.06	4.07	4.40	7.34	9.52	25.9	25.2	25.1	Heat, industry
Gasification to ethanol 61.8 MMGPY / mixed alcohol 76.2 MMGPY	Chips								100.1	35.0	Cellulosic bio-ethanol
	Forest industry residues					29.3				38.1	
	Hog fuel						23.5			30.5	
	Slash	26.8	27.4	25.2	56.7	11.9	2.2	52.6	39.7	121.7	
	Chips									65.1	FT diesel, electricity

Fischer-Tropsch. catalytic. hydro-processing. high temperature. flow gasifier.41.7 MGPY	Slash		1.21	42.4

[a, b] (Moret *et al.*, 2017)

[c] (Wright et Brown, 2019 ; Phillips *et al.*, 2007)

[d] (Swanson *et al.*, 2010)

2.3.6 Mitigation costs

Figure 2.10 shows the marginal abatement cost for the reduction scenarios. Until 2030, marginal abatement costs remain moderate ($62 and $116 per ton CO_2-eq in GHGA and GHGB, respectively). Afterwards, costs increase significantly to reach by 2050 $615 and $1326, respectively. These are significantly high carbon prices, to be paid by a small number of economic agents (since the energy system is by 2050 extensively decarbonized). However, TIMES is only a partial equilibrium model (looking at energy markets) (Bahn, 2018). It cannot handle the full economic effect of these high prices, beyond the assumed price elasticity of demand for energy services. To do so, one would rather need to use, e.g., a general equilibrium model, which is beyond the scope of this paper.

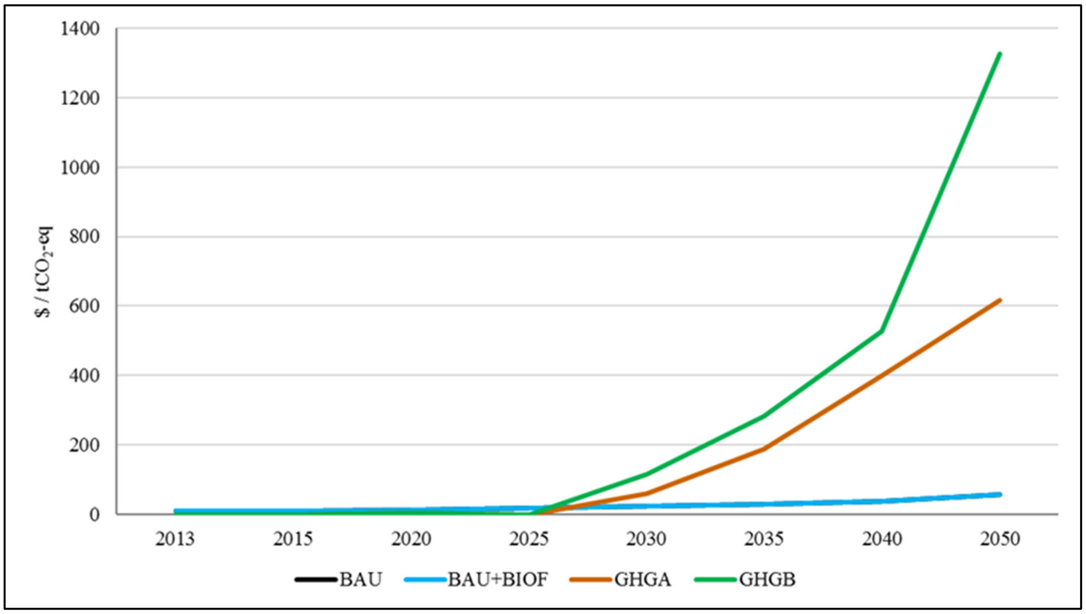

Figure 2.10 Marginal abatement cost for one ton of CO_2-eq in Quebec

2.3.7 Sensitivity analysis

Three scenarios with a feedstock price decrease (GHGB-X%) and three other scenarios with a feedstock price increase (GHGB+X%) are considered to assess the effect of feedstock price fluctuations on bioenergy production. Figure 2.11 shows the feedstock price effect on bioenergy production in the stringent GHG reduction scenario of GHGB in 2050. Total bioenergy increases by around 12% to 20%, with a cost decrease of the forest-based feedstock of 20% to 35% (GHGB-20%, GHGB-35%), respectively. A feedstock price reduction of 50% yields a similar increase of 20%. The main reason for this is the limited availability of forest-based feedstocks. Besides, the amount of cellulosic bioethanol, and bio-based heat and electricity are all increased in the GHGB-X% scenarios compared to the base case (GHGB). Conversely, the amount of bioenergy production decreases by 0.5% when raising feedstock price by 20% (GHGB+20%). Whereas it is reduced by about 7% to 10% when increasing feedstock price by 35% to 50% (GHGB+35%, GHGB+50%), respectively. The solution is thus more sensitive to a price decrease than an increase. Overall, bioenergy production is not sensitive to feedstock's price increase of 20% (or less), as it remains a competitive option to abate GHG emissions. Afterwards, the amount of bioenergy does reduce with growing feedstock price as it loses its competitiveness.

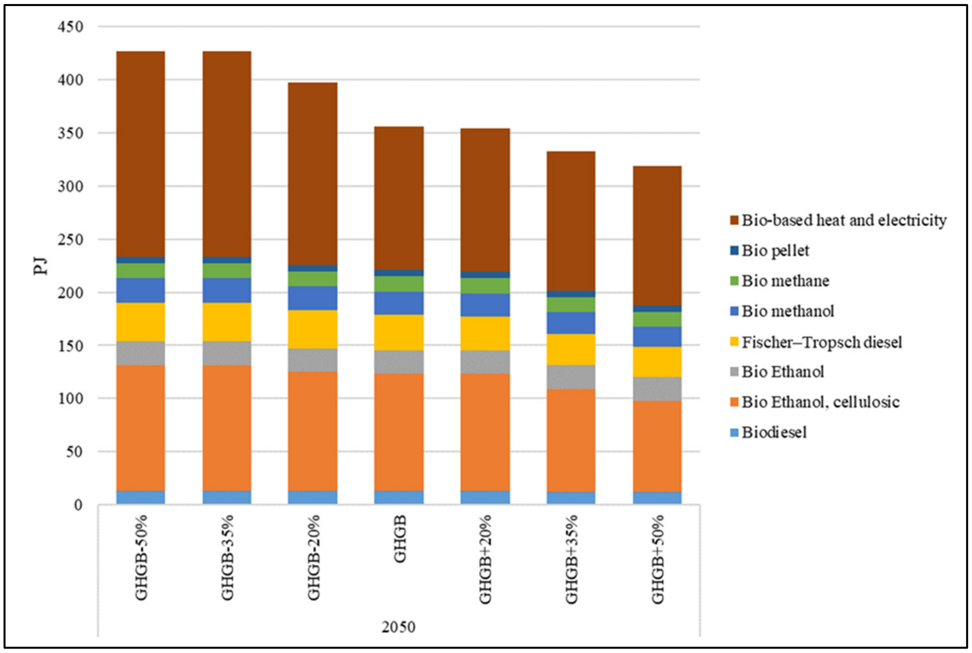

Figure 2.11 Bioenergy production at different prices of feedstock in GHGB scenario in 2050 in Quebec

2.4 Discussion

It has been assumed that getting more feedstocks is achievable at a higher price, which can affect the forest-industry market. However, this study does not consider forest stands, and NATEM-Quebec does not consider biomass competition between industrial usage and bioenergy production. Based on (Ghafghazi *et al.*, 2017), the only feedstock that can have competition for board production in Canada is forest industry residues. This latter paper points out that surplus mill residues in Canada, and particularly in the eastern provinces, are limited. Besides, increasing future demand for feedstocks above expected sustainable supply can lead to indirect land-use change and raise the competition with alternative biomass applications with superior carbon sequestration profiles (Allen *et al.*, 2016). To increase feedstock availability at least cost, the harvest rate of residues and salvage trees could be increased and slash burning could be completely prohibited (Smyth *et al.*, 2014). Also, surplus forest growth (low-quality roundwood) is achievable as a potential source of feedstock, which can, in turn, strengthen the forest value chain (Durocher *et al.*, 2019).

Biogenic CO_2 emissions from biomass consumption have been treated as carbon neutral. However, bioenergy systems can lead to positive, neutral or negative effects on biogenic carbon stocks, contingent upon the bioenergy system's characteristics, soil and climate factors, vegetation cover, and land-use history (Berndes *et al.*, 2016). The authors acknowledge this limitation of the current study and plan to address it in a forthcoming research project.

Compared with first-generation biofuels that are mainly produced from agriculture crops and considered a threat to food security, second-generation biofuels that are generally derived from lignocellulosic feedstock are more available, low-priced, and sustainable. New conversion technologies allow a high conversion efficiency of these residues. (Phillips *et al.*, 2007) and (Wright et Brown, 2019) have shown that forest-based feedstock could be converted to bioethanol in a cost-competitive way using gasification to cellulosic bioethanol conversion technology. Fischer-Tropsch catalytic conversion technology with high-temperature gasification (Swanson *et al.*, 2010) consumes lignocellulosic-based sources to produce liquid fuels (FT diesel). FT diesel has a similar quality to those derived from petroleum and can be utilized as liquid transportation fuels in different sectors. Industrial and district boilers (Moret *et al.*, 2017) have been utilized over time to meet low emission heat requirements in the industrial and commercial sectors, respectively. Choosing a suitable conversion process mainly depends on the type of available biomass, characteristics of the final bioenergy, and existing infrastructure. For instance, advanced alcohols are suitable for drop-in fuels in current spark ignition gas engines. Moreover, these biofuels are compatible with the current fuel distribution system too. Any bioenergy pathway should be evaluated given its regional energy context because each region has unique energy systems and socio-economic conditions.

The goal of achieving an 80% GHG emission reduction in Quebec has been considered in previous studies (Astudillo, 2019 ; Vaillancourt *et al.*, 2017 ; Vaillancourt, Bahn et Levasseur, 2019). They have stated that an 80% GHG emission reduction target is not achievable with the current technologies considered in NATEM without any change in the (useful) demand for energy services such as passenger-kilometers and ton-kilometers traveled. In our study, the

80% reduction target is achieved though improving energy efficiency using technological alternatives, decarbonization of electricity generation, massive electrification, and large-scale deployment of bioenergy. Investing in negative emission technologies should also be part of the solution and will be considered in a forthcoming study.

Declining demand for traditional forest products across many countries such as the US, Canada, and Nordic countries leads to developing new products such as forest-based bioenergy. The GHG emission reduction potential of forest-based bioenergy provides further incentives. As discussed earlier, it is a storable energy solution, compatible with the existing fossil infrastructure, and does not threaten food security. Such second-generation biofuels are thus more socially acceptable (Hurmekoski *et al.*, 2018 ; Jåstad *et al.*, 2019 ; Xu *et al.*, 2018 ; Longstaff *et al.*, 2015 ; Allen *et al.*, 2016 ; Van Walsum et Wheeler, 2013). According to this study, forest-based bioenergy is an indispensable resource for transitioning to a low carbon economy. This conclusion should apply as well to countries with an important forest-based economic sector. Besides, the modeling approach used for forest-based bioenergy, based on the concept of a reference energy system that details energy commodities and technologies, can be easily adapted to other regional context by updating resource prices and eventually technology-related costs. In particular, one could envision to adapt the modeling presented in Figure 2.1 in any of the 70 countries using a TIMES approach. As a reminder, detailed techno-economic data is given in APPENDIX I (Part A).

2.5 Conclusion

The objective of this study was to measure the long-term role of forest-based bioenergy technologies using a bottom-up energy model (NATEM-Quebec). For this purpose, a comprehensive overview of bioenergy conversion processes has been accomplished, and the required data has been collected in the context of Quebec, a Canadian province. Using NATEM-Quebec, four scenarios have been evaluated: two business-as-usual scenarios (BAU, BAU+BIOF), and two GHG emission reduction scenarios (GHGA, GHGB).

This study shows that transportation is the primary contributor to GHG emissions over the time horizon in all scenarios, except for GHGB in 2050. The industrial sector is the main emitter by 2050 in GHGB, indicating the difficulties to decarbonize heavy industry. Furthermore, an extensive electrification is required to reach the GHG reduction targets. The bioenergy share is expected to increase considerably in the transportation and industrial sectors, cutting down on the need to reduce GHG emissions. Forest-based bioenergies such as cellulosic bioethanol, biobased heat, FT diesel and electricity as a co-product can effectively support this energy transition.

Quebec's government envisions a 50% increase in bioenergy production by 2030 relative to the 2013 level (Government of Québec, 2020). However, NATEM computes a bioenergy expansion of 75% for the GHGA and 114% for the GHGB scenarios in 2030 compared to the BAU scenario in 2013. Therefore, a greater penetration of bioenergy could be envisaged by Quebec's government in its 2030 plan for a green economy. This study reveals that forest-based bioenergy should be an important component of the decarbonization strategy of Quebec. Other world regions with a declining trend for traditional forest products should also consider such a strategy. Future research should address the limitations of this present study, such as additional feedstock availability and treating biogenic CO_2 emissions as carbon neutral that may bias the results.

CHAPTER 3

IMPACT OF BIOGENIC CARBON NEUTRALITY ASSUMPTION FOR ACHIEVING A NET-ZERO EMISSION TARGET: INSIGHTS FROM A TECHNO-ECONOMIC ANALYSIS

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Abstract

Global pathways limiting warming to 2°C or below require deep carbon dioxide removal through a large-scale transformation of the land surface, an increase in forest cover, and the deployment of negative emission technologies (NETs). Government initiatives endorse bioenergy as an alternative carbon-neutral energy source for fossil fuels. However, this carbon neutral assumption is increasingly being questioned, with several studies indicating that it may result in accounting errors and biased decision-making. To address this growing issue, we use a carbon budget model combined with an energy system model. We show that including forest sequestration in the energy system model alleviates the decarbonization effort. We discuss how a forest management strategy with high sequestration capacity reduces the need for expensive negative emission technologies. This study indicates the necessity of establishing the most promising forest management strategy before investing in bioenergy with carbon capture and storage (BECCS). Finally, we describe how a carbon neutrality assumption may lead to biased decision-making because it allows the model to use more biomass without being constrained by biogenic CO2 emissions. The risk of biased decision-making is higher for regions that have lower forest coverage since available forest sequestration cannot sink biogenic emissions in the short-term, and importing bioenergy could worsen the situation.

Keywords: Negative emissions technologies; terrestrial sequestration; biogenic carbon; energy system decarbonization; TIMES model

3.1 Introduction

The current nationally determined contributions (NDCs) until 2030 make it impossible to limit warming to 1.5°C with no or limited overshoot, and make it more difficult to limit warming to 2°C after 2030 (Riahi *et al.*, 2022). Climate change mitigation pathways that limit warming to 2°C or below require deep carbon dioxide removal through a large-scale transformation of the land surface, an increase in forest cover, and the deployment of negative emission technologies (NETs) (Riahi *et al.*, 2022 ; Lecocq *et al.*, 2022). Four NETs are ready for large-scale deployment, namely, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and storage (BECCS). These NETs incur low to moderate costs (\$100/t CO_2 or less) and have significant potential for safe scale-up from present implementation (NASEM, 2019). A low cost is defined as a range between 0-20 \$/t CO_2, while a moderate cost is defined as a range between 20-100 \$/t CO_2 (NASEM, 2019). Although, these costs for BECCS may be higher due to uncertainty regarding the parasitic energy load of CCS systems (Woolf, Lehmann et Lee, 2016 ; Fajardy et Mac Dowell, 2017). Direct air capture (DAC) is another emerging NET option, although its costs are still prohibitively high (NASEM, 2019 ; Babiker *et al.*, 2022). Carbon storage through the increased usage and preservation of harvested wood products (HWP) is also an available near-term approach for removing CO_2 (Churkina *et al.*, 2020 ; Pomponi *et al.*, 2020 ; Mishra *et al.*, 2022 ; NASEM, 2019).

Carbon dioxide removal (CDR) can be accomplished through forestry practices such as intensifying afforestation/reforestation, and improving forest management strategies (NASEM, 2019). The major limitation of CDR through in forest carbon storage is the demand for wood that limits possible reductions in harvest rate, and the inability to fully implement forest management practices (NASEM, 2019). A forest managed for wood production may store less carbon than a forest that is left unharvested. However, disturbances may reduce the amount of carbon stored in unharvested boreal forests. Demand for wood can also support CDR via in-forest carbon storage as landowners maypre invest more in forest management (Favero, Baker, *et al.*, 2023 ; Wade *et al.*, 2022 ; Daigneault *et al.*, 2022 ; Abt, Galik et Baker, 2022). While CO_2 sequestered by forestry practices can be stored for decades, the associated sinks will gradually become saturated (Riahi *et al.*, 2022 ; Lecocq *et al.*, 2022). BECCS plays an essential role in most climate change mitigation pathways limiting global temperature to 2°C or below (Hanssen *et al.*, 2020). However, the deployment of BECCS must incorporate the numerous strategies in which forests and forest-related sectors contribute to CDR because there could be trade-offs between carbon sequestration, storage, and biomass production, as well as between short-term and long-term GHG reduction targets (Berndes *et al.*, 2016). According to ref. (Hanssen *et al.*, 2020), the IPCC's projected CO_2 sequestration through BECCS is achievable biophysically, although, given its extensive land requirements, a much more limited and earlier deployment was recommended.

Carbon that is taken up, sequestered, or released by biomass is known as biogenic carbon (Berndes *et al.*, 2016). Biogenic CO_2 emissions from bioenergy sources, according to the IPCC (Eggleston *et al.*, 2006), should not be included in the energy sector of national greenhouse gas inventories since all biogenic emissions and uptakes are accounted for in the Agriculture, Forestry, and Other Land-Use (AFOLU) sector. Accordingly, government initiatives endorse bioenergy as an alternative carbon-neutral energy source for fossil fuels (Liu *et al.*, 2017). This could lead to accounting errors in jurisdictions where carbon flows from the AFOLU sector are not included in GHG emissions inventories. Governments also rely on energy system models to explore potential decarbonization pathways. Biogenic CO_2 is assumed neutral in many studies, including our latest one (Kouchaki-Penchah *et al.*, 2022) in which a techno-economic model of the energy system is used to show that forest-based bioenergy is a feasible decarbonization pathway for regions, such as Canada, with a declining trend for traditional forest products. The carbon neutrality assumption might be acceptable when the rotation length of biomass is short such as annual crops. The assumption, however, may not remain true when the sequestration period is lengthy, as in the case of forest trees (Cherubini *et al.*, 2011 ; Guest *et al.*, 2013). Bioenergy systems can lead to positive, neutral, or negative effects on biogenic carbon stocks (Berndes *et al.*, 2016). The carbon-neutrality assumption is increasingly being questioned, with several studies indicating that it may result in accounting errors and biased decision-making (Berndes *et al.*, 2016 ; Liu *et al.*, 2017 ; Albers *et al.*, 2019).

Many studies (Head *et al.*, 2019 ; Smyth *et al.*, 2014 ; Smyth *et al.*, 2017 ; Werner *et al.*, 2010 ; Cintas *et al.*, 2017 ; Gustavsson *et al.*, 2017 ; Lamers *et al.*, 2014 ; Moreau *et al.*, 2022 ; Landry *et al.*, 2021 ; Babí Almenar *et al.*, 2023) have evaluated the role of forest management or bioenergy in climate change mitigation using modeling frameworks that simulate the dynamics of forest carbon stocks. However, these studies cannot assess the most cost-effective pathways to reduce GHG emissions. Several research efforts (Börjesson *et al.*, 2014 ; Dodder *et al.*, 2015 ; König, 2011 ; Panos et Kannan, 2016 ; Zhao *et al.*, 2015 ; Jåstad *et al.*, 2021 ; Hugues, Assoumou et Maizi, 2016 ; Levasseur *et al.*, 2017 ; Vaillancourt, Bahn et Levasseur, 2019) have employed energy system models to examine the role of bioenergy while taking into account market competition among different pathways (see Kouchaki-Penchah et al. (2022)), but they usually disregard the dynamics of soil organic carbon and land use (Frank *et al.*, 2015) and follow a carbon neutrality assumption. Several studies (Baker *et al.*, 2019 ; Kim *et al.*, 2018 ; Favero, Daigneault, *et al.*, 2023 ; Favero, Baker, *et al.*, 2023 ; Favero, Daigneault et Sohngen, 2020) have utilized the global timber model, a partial equilibrium model designed to optimize overall welfare in timber markets, to analyze the connection between long-term changes in biomass demand and carbon sequestration. Funk et al. (2022) used a combination of GLOBIOM, a bottom-up partial equilibrium model for the agriculture, forestry, and bioenergy sectors, and carbon flux data from the NASA Carbon Monitoring System to investigate the magnitude and risks of unaccounted emissions. The study particularly focused on the demand for wood pellets under various levels of climate mitigation targets across major trading regions. The authors of the study discovered that bioenergy production could be advanced beyond the optimal level for the climate or the health of forests due to potential increases in unaccounted emissions from the harvest of biomass feedstocks, which are enabled by accounting rule artifacts. TIMES-MIRET, a partial-equilibrium model, has been used in combination with a dynamic biogenic carbon modeling tool to conduct a consequential life cycle assessment (LCA) of policy-driven transportation strategies for France (Albers *et al.*, 2019). In this case, the dynamic biogenic carbon modeling tool was used separately to calculate the biogenic carbon inventory of the biomass resources with long rotation lengths that had previously been fed into TIMES-MIRET. TIMES model has also been used combined with an environmentally extended input-output model to estimate indirect CO_2 emissions (Daly *et al.*, 2015), as well as LCA to fully assess the environmental impact of the energy system (Fernández Astudillo *et al.*, 2019).

Our work builds upon the full integration of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (W.A. Kurz *et al.*, 2009), an aspatial, stand- and landscape-level modeling framework, and the North American TIMES Energy Model (NATEM) (Vaillancourt *et al.*, 2017), a bottom-up techno-economic model of the energy system, to overcome the limitations of the other approaches. We use the output of CBM-CFS3 to model forest management approaches that would lead to different biomass availability for bioenergy and net forest carbon stocks and emissions, to see if and how this biomass would be used within the energy system over the considered time horizon. In addition, we provide a detailed modeling of different forest-based bioenergy and BECCS pathways. In this manuscript, we consider the specific situation of the province of Quebec (Canada). GHG emissions and uptakes associated with different forest management and BECCS approaches from CBM-CFS3 are integrated into NATEM-Quebec to evaluate potential decarbonization pathways by 2050. It is the first time that biogenic CO_2 flows are being modeled in an energy system model like TIMES.

3.2 Methodological approach

3.2.1 Forest modeling framework

The forest analysis was carried out using the CBM-CFS3 model (W.A. Kurz *et al.*, 2009) based on Moreau et al. (2023). It simulates the effects of land-use change and serves as a means to account for land-use change impacts under the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol requirements and the according to IPCC's relevant guidelines. The CBM-CFS3 is a yield data-driven model that explicitly simulates the dynamics of forest carbon stocks and stock changes in above- and belowground biomass and dead organic matter pools. It also can simulate disturbances such as forest management operations, land-use change, wildfires, and insect outbreaks (see W. A. Kurz et al. (2009) for a detailed description). Ecosystems outside Canada (Duffy *et al.*, 2021) can also benefit from the CBM-CFS3 by adjusting the default Canadian ecological parameters and data in the database powering the model. Provincial forest data for the Quebec region were acquired from the National Inventory Report (NIR) of Canada (Environment and Climate Change Canada, 2021). Detailed data on fire and spruce budworm (SBW), as natural disturbances prior to 2018, were implemented within the simulation. However, a mean value based on data from the previous decades was used for the 2019-2050 time horizon, owing to the inability to predict fire and SBW outbreaks; the approach is described in ref. Moreau et al. (2022).

3.2.2 TIMES modeling approach

The TIMES model is an evolution of the MARKAL model developed within the IEA ETSAP program that combines MARKAL and EFOM approaches (R Loulou, Goldstein, Kanudia, Lettila, et al., 2016). A bottom-up model uses a disaggregated approach to represent the energy system of a given jurisdiction, and is well suited to describe systems with emerging energy sources (Bahn, 2018). A detailed reference energy system (RES) is defined to describe different energy carriers and technologies from primary energy production to final energy consumption. Demands for energy services are exogenously implemented to deploy a wide range of end-use technologies that use different types of final energy (Bahn et Vaillancourt, 2020). TIMES is cast as a linear programming model. It minimizes the loss of total surplus by concurrently making technology investment and operation, primary energy supply, and energy trade choices for each region (R Loulou, Goldstein, Kanudia, Lettila, et al., 2016), to satisfy final energy demands. Decision variables (energy technologies and commodities) denote choices to be made endogenously. Constraints here are the physical and logical interactions that must be addressed in order to accurately depict the entire energy sector (R Loulou, Goldstein, Kanudia, Lettila, et al., 2016). Nationally determined contributions and GHG emission reduction targets can also be implemented as policy constraints. See R Loulou, Goldstein, Kanudia et Leh, (2016) for a complete documentation of TIMES.

3.2.3 NATEM model

The North American TIMES Energy Model (NATEM) follows a TIMES approach to model the Canadian energy sector. NATEM includes 70 end-use demands for energy services in different agriculture, commercial, industrial, residential, and transportation sectors (see Vaillancourt et al. (2017)). A thorough representation of Quebec's energy system has been derived from NATEM in order to build a harmonized model with CBM-CFS3. The spatial scale of this sub-model, which we call NATEM-Quebec, covers the whole province, with data disaggregated by sub-regions. NATEM-Quebec is calibrated to a 2016 base year, with a 2060 time horizon divided into 9 periods and 16 annual time slices. A global yearly discount rate of 5% is applied (Vaillancourt, Bahn et Levasseur, 2019), and all costs are based on 2016 Canadian dollars (CAD). NATEM-Quebec comprises over 4000 different energy technologies, 800 commodities, and 700 user constraints. The VEDA2.0 model management system (KanORS-EMR, 2023), which provides input to the TIMES code, reads data and assumptions included in NATEM-Quebec. The TIMES code runs in the GAMS (GAMS, 2023) environment, resulting in an LP problem with over 300,000 equations and approximately

400,000 variables. The CPLEX solver is used to optimize this LP problem (KanORS-EMR, 2023).

3.2.4 Integration approach

Three forest management strategies were chosen for this study: FM1 depicts a business-as-usual scenario, whereas FM2 and FM3 represent intensification and conservation scenarios, respectively. Conservation and intensification approaches were adopted based on an increasing or decreasing harvest volume gradient compared to a business-as-usual strategy. The FM1 strategy includes NIR-2018 dataset (Environment and Climate Change Canada, 2021) assumptions for Quebec, with minor modifications, to show the current provincial forest management strategy. FM2 delivers the maximum feedstocks, and the lowest forest carbon stock or carbon sequestration, whereas FM3 produces less biomass and higher carbon sequestration by reducing the harvest. In comparison to the business-as-usual strategy, the FM2 or residues strategy covers additional reforestation of 15,000 ha/year, up to 16 Mm^3/year of extra harvest, a further commercial thinning of 10%, and an increased residues harvest of 1.2 Mtma/year. The FM3 strategy, with a smaller harvest, reduces the harvest volume to up to 10 Mm^3/year through extracting less wood from the same area without changing rotation and reforestation as compared to business-as-usual (Moreau *et al.*, 2023). The selected forest management strategies do not include any measures beyond reforestation to improve productivity in forest ecosystems. However, ref (Ménard, Thiffault, Kurz, *et al.*, 2022 ; Ménard, Thiffault, Boulanger, *et al.*, 2022) outline additional approaches for enhancing forest growth in Quebec. An intensification strategy can include increased clearcut harvesting and increased procurement of low-quality trees that are part of the allowable annual cut but have been left standing because their fiber does not meet the requirements of sawmills and pulp mills (Durocher *et al.*, 2019). Accordingly, FM2 adheres to the provincial annual allowable cut, which is the maximum volume of industrial roundwood that can be sustainably harvested each year. The literature (Kurz *et al.*, 2013 ; Paradis, Thiffault et Achim, 2019 ; Senez-Gagnon *et al.*, 2018) has extensively demonstrated that clearcutting causes a phase of net emissions to the atmosphere in boreal and northern temperate stands in the years following harvesting since the emissions resulting from decomposition are considerably higher than the annual sequestration driven by photosynthesis, a pattern that can persist for 10 to 30 years.

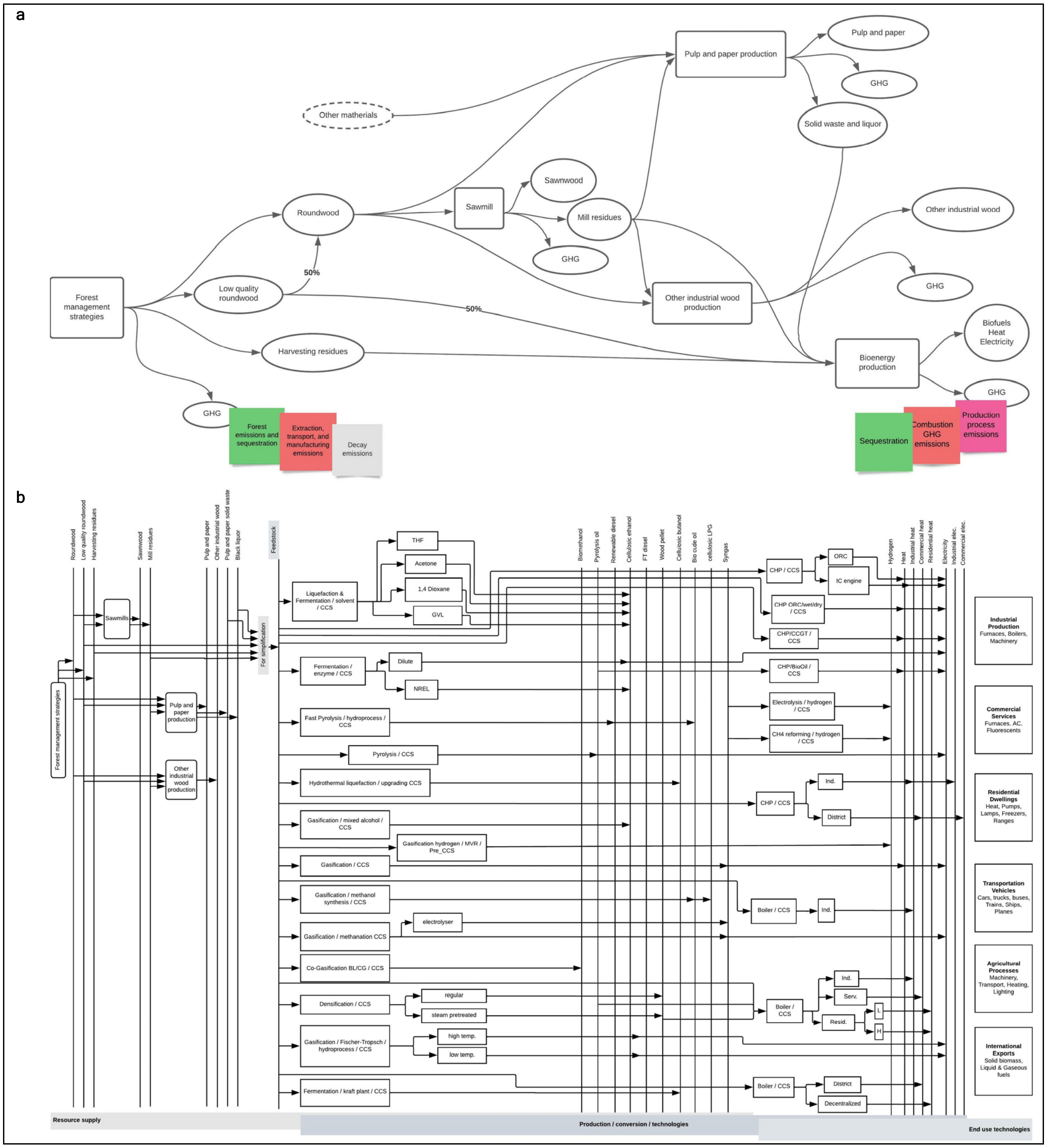


Figure 3.1 (a) Defined supply chain in NATEM, (b) reference energy system of forest-based bioenergy technologies with and without CCS (BIOF)

Carbon stocks in tC from the CBM-CFS3 model are converted into t wood using a generic value of 50% for wood carbon content (Wenzl, 1970).The biomass is distributed following the forest product supply chain shown in Figure 3.1(a) to meet the demands for primary and secondary industries, as well as bioenergy production. CBM-CFS3 results detailing the amount of carbon transferred to harvested wood products and bioenergy are input to the NATEM-Quebec model to investigate biomass usage in the energy system throughout the time horizon. A supply curve with relative availability and costs for each feedstock has been defined in NATEM-Quebec.

In this research, biogenic emissions of forest-based biomass along with extraction, transport, and manufacturing missions are modeled in NATEM for the first time. Other forms of biomass, such as annual crops and short rotation energy crops, are still assumed to be carbon neutral. This means that biogenic CO_2 released by combustion is considered absorbed from the atmosphere shortly before harvest. Biogenic carbon flows associated with these biomass sources could be added in the future to assess the climate mitigation potential of NETs related to the storage of carbon in agricultural soils (Agostini, Giuntoli et Boulamanti, 2014). Decomposition emissions occur in future years based on W.A. Kurz et al. (2009). These emissions happen when harvesting residues or low-quality roundwood are left in the forest (at no cost).

Techno-economic data for 94 forest-based bioenergy technologies with and without CCS from various literature sources are modeled in NATEM (BIOF). Figure 3.1(b) depicts the BIOF reference energy system used in NATEM. These technologies mainly use biochemical conversion processes such as fermentation, or thermochemical conversion processes such as gasification or pyrolysis methods. The present research also takes into account densification as a mechanical conversion process, as well as various forms of combined heat and power (CHP), boiler, electrolysis, and methane reforming as secondary conversion processes. Available bioenergies include cellulosic ethanol, butanol, methanol, and cellulosic liquified petroleum gas, as well as pyrolysis oil, bio-crude oil, renewable diesel, FT diesel, wood pellet, syngas, hydrogen, bioheat, and electricity.

For bioenergy technologies without CCS, technologies from our previous study were used, and related costs updated (Kouchaki-Penchah *et al.*, 2022). For BECCS, post-combustion CCS (Berghout *et al.*, 2015) was coupled with bioenergy technologies from our previous study (Kouchaki-Penchah *et al.*, 2022) by adding required energy, extra investment costs, and fixed and variable operating costs of CCS to each of the technologies. In addition, three bioenergy technologies using pre-combustion CCS (Tock, 2013) were modeled. A CO_2 capture ratio of 90% was considered for Post-combustion CCS (Berghout *et al.*, 2015). Three CO_2 capture ratios were considered for pre-combustion CCS: 47%, 65%, and 67% (Tock, 2013). Even though recent studies (Cormos, 2023 ; Poluzzi, Guandalini et Romano, 2022) suggest higher capture efficiency of up to 98%, more conservative capture efficiencies were used to ensure comparability with other research studies. Complete techno-economic data may be found in the Supplementary_Information_BIOF.xlsx file. (Kouchaki-Penchah *et al.*, 2022) also describes bioenergy conversion pathways.

Previously, NATEM completely ignored biogenic CO_2 emissions as they were considered to be neutral. BECCS could capture CO_2, and this “Captured CO_2” was seen as a negative amount in total GHG emission calculations. In the present study, forest-based BECCS are no longer regarded as negative emission technologies as biogenic CO_2 from forest management, biomass combustion and decomposition are already accounted for. In this case, CCS allows avoiding a biogenic CO_2 emission instead of capturing CO_2 from the atmosphere.

This study takes into account two sets of scenarios. The first set evaluates the integration of alternative forest management strategies and biogenic carbon into NATEM, and the second examines the contribution of bioenergy and BECCS in attaining net-zero emissions by 2050. Scenario REF_CN presents a business-as-usual scenario without a net-zero emission target, forest management, biogenic carbon and forest-based BECCS. Scenario GHG_CN adds GHG emission reduction targets of 37.5% by 2030 (1990 level) and net-zero by 2050 to the REF_CN scenario. Accordingly, other scenarios were built by including/excluding forest management, biogenic carbon and forest-based BECCS (Table 3.1) to these two reference scenarios. Scenarios identified with "FM-CN" adopt a forest management strategy, but do not account for biogenic CO_2 emissions. In these cases, biomass availability for bioenergy depends on the forest management strategy, but the biogenic carbon balance is considered neutral. Scenarios identified with "NO-BIOF" exclude forest-based bioenergy and BECCS (in APPENDIX II (part A)) while accounting for biogenic CO_2 emissions.

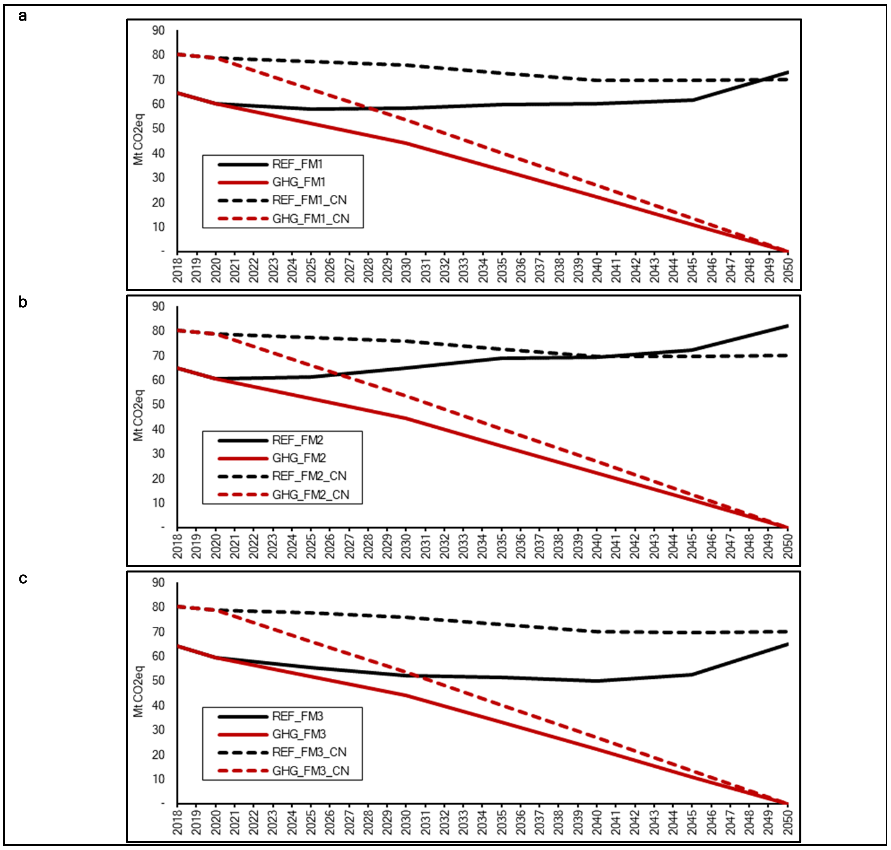
Table 3.1 Considered scenarios

Scenario	Forest management	Biogenic carbon	Carbon neutral	Forest-based BECCS	Net-zero emission by 2050
REF_CN			*		
REF_FM1	*	*		*	
REF_FM1_NO_BIOF	*	*			
REF_FM1_CN	*		*	*	
REF_FM2	*	*		*	
REF_FM2_NO_BIOF	*	*			
REF_FM2_CN	*		*	*	
REF_FM3	*	*		*	
REF_FM3_NO_BIOF	*	*			
REF_FM3_CN	*		*	*	
GHG_CN			*		*
GHG_FM1	*	*		*	*
GHG_FM1_NO_BIOF	*	*			*
GHG_FM1_CN	*		*	*	*
GHG_FM2	*	*		*	*
GHG_FM2_NO_BIOF	*	*			*
GHG_FM2_CN	*		*	*	*
GHG_FM3	*	*		*	*
GHG_FM3_NO_BIOF	*	*			*
GHG_FM3_CN	*		*	*	*

3.3 Result analysis

3.3.1 Forest carbon management effects on GHG emission trajectories

Carbon neutral scenarios have higher net GHG emissions in the first years than scenarios considering biogenic carbon (Figure 3.2(a, b, c)) as the former ignore forest sequestration. Taking forest sequestration into account increases the model's ability to decarbonize the system. For example, in 2040, REF_FM1 has a total GHG emission of 60 Mt CO_2-eq, while it is close to 70 Mt CO_2-eq for REF_FM1_CN. In our view, this should not be interpreted as postponing decarbonization. It should rather be seen as an opportunity to flatten the GHG trajectories. REF_FM2 shows higher GHG emissions than its carbon neutral counterpart (REF_FM2_CN) after 2040 (Figure 3.2(b)) because available forest sequestration cannot entirely offset biogenic CO_2 emissions. Carbon stock decreases with intensification because logging creates a carbon debt, where emissions exceed sequestration. The dead organic matter in the ecosystem is being decomposed, and the photosynthesis from tree regeneration is not large enough to compensate. For example, it can take up to 30 years to achieve net ecosystem sequestration after a clear-cut in the boreal forest. Therefore, at the provincial level, an increase in logging operations can result in emissions for a couple of decades, as suggested by ref. (Moreau *et al.*, 2023). This occurs later for FM1 and FM3 because of their higher sequestration capacities. Choosing a suitable forest management strategy with high sequestration capability provides an opportunity to alleviate the decarbonization effort. For instance, REF_FM3 shows the lowest GHG emissions in 2050 (64.7 Mt CO_2-eq; Figure 3.2(c)) among reference scenarios, including a forest management strategy. This is because FM3 has the highest sequestration capability, reducing pressure on the energy system to achieve a net-zero emission by 2050 (GHG_FM3). Including biogenic emissions allows the model to use available forest sequestration for difficult-to-decarbonize sectors such as the heavy industry in GHG scenarios in 2050 (see Figure A-II 1 in APPENDIX II). Therefore, it alleviates the reduction effort and provides policymakers with the flexibility to allocate negative emissions obtained from forest sequestration (e.g., through a system of carbon offsets)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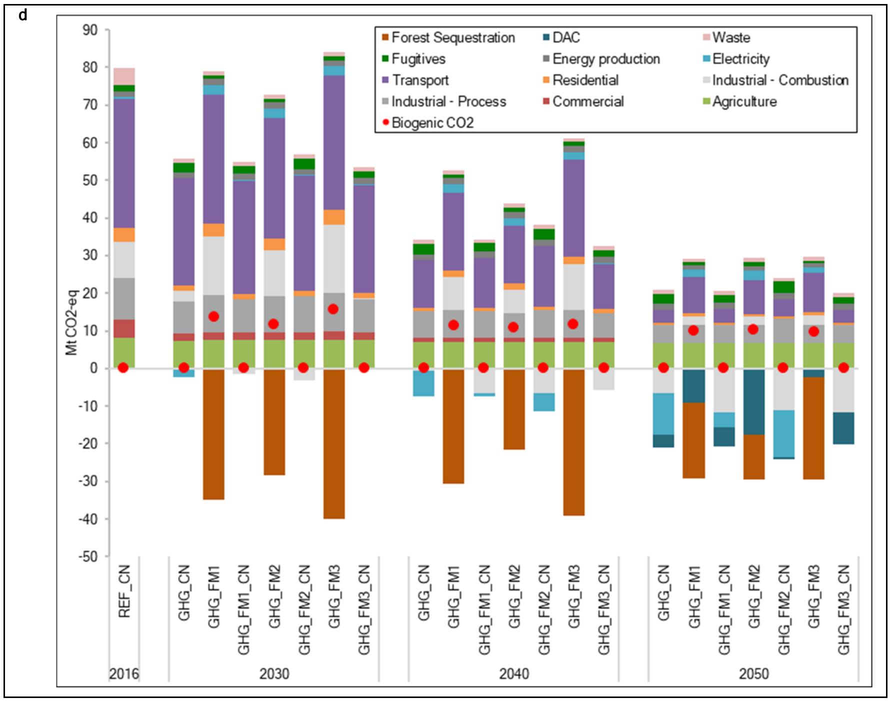

Figure 3.2 Total net GHG emissions in Quebec, (a) FM1 (BAU), (b) FM2 (intensification), (c) FM3 (conservation), (d) total GHG emissions by sector in Quebec under a carbon neutrality assumption

After 2030 (Figure 3.2(d)), GHG scenarios assuming biogenic carbon neutrality (GHG_CN, GHG_FM1_CN, and GHG_FM2_CN) rely on capturing and sequestering CO_2 from biomass consumption through BECCS, which is seen as a negative amount in GHG calculations. To achieve net-zero emissions in 2050, the need for DAC is inevitable and depends on available forest sequestration. For instance, in 2050, GHG_FM2_CN relies less on DAC (less than 1 Mt CO_2-eq) than other scenarios. This does not mean that the FM2 forest management strategy offers the best pathway in terms of lower investments in DAC since including biogenic emissions and uptakes (GHG_FM2) increases the need for DAC (18 Mt CO_2-eq). Therefore, disregarding biogenic carbon leads to biased decision-making. GHG_FM3 shows the lowest need for DAC (2 Mt CO_2-eq) among scenarios that consider biogenic CO_2 due to higher forest sequestration. In our view, this makes FM3 the most promising forest management strategy to achieve net-zero emissions by 2050, considering that DAC is facing practical barriers to a pace of scale up. Figure A-II 2 and Figure A-II 3 in APPENDIX II illustrate total GHG emissions in Quebec by sector for the first and second sets of scenarios, respectively.

3.3.2 Implication for renewable energies and hydrogen

Figure 3.3(a) shows primary energy from hydroelectricity, biomass and other renewables (e.g., wind and solar). In 2050, other renewables account for more than 20% of total primary energy production in all GHG scenarios considering biogenic CO_2 emissions and uptakes. Also, the biomass share of total primary energy production is 12% and 11% for GHG_FM1 and GHG_FM3, respectively. Due to the high availability of feedstocks, this rises to 15% for GHG_FM2. The assumption of carbon neutrality increases biomass production between 34% to 45% for each GHG scenario with a forest management strategy depending on the available biomass. As a reminder, in carbon-neutral scenarios, there are no biogenic CO_2 emissions, and even using biomass may result in negative emissions (BECCS). Except for GHG_FM3_CN, which confronts a scarcity of biomass supply, biomass is anticipated to grow in the carbon neutral GHG reduction scenario compared to the REF_CN scenario in 2050.

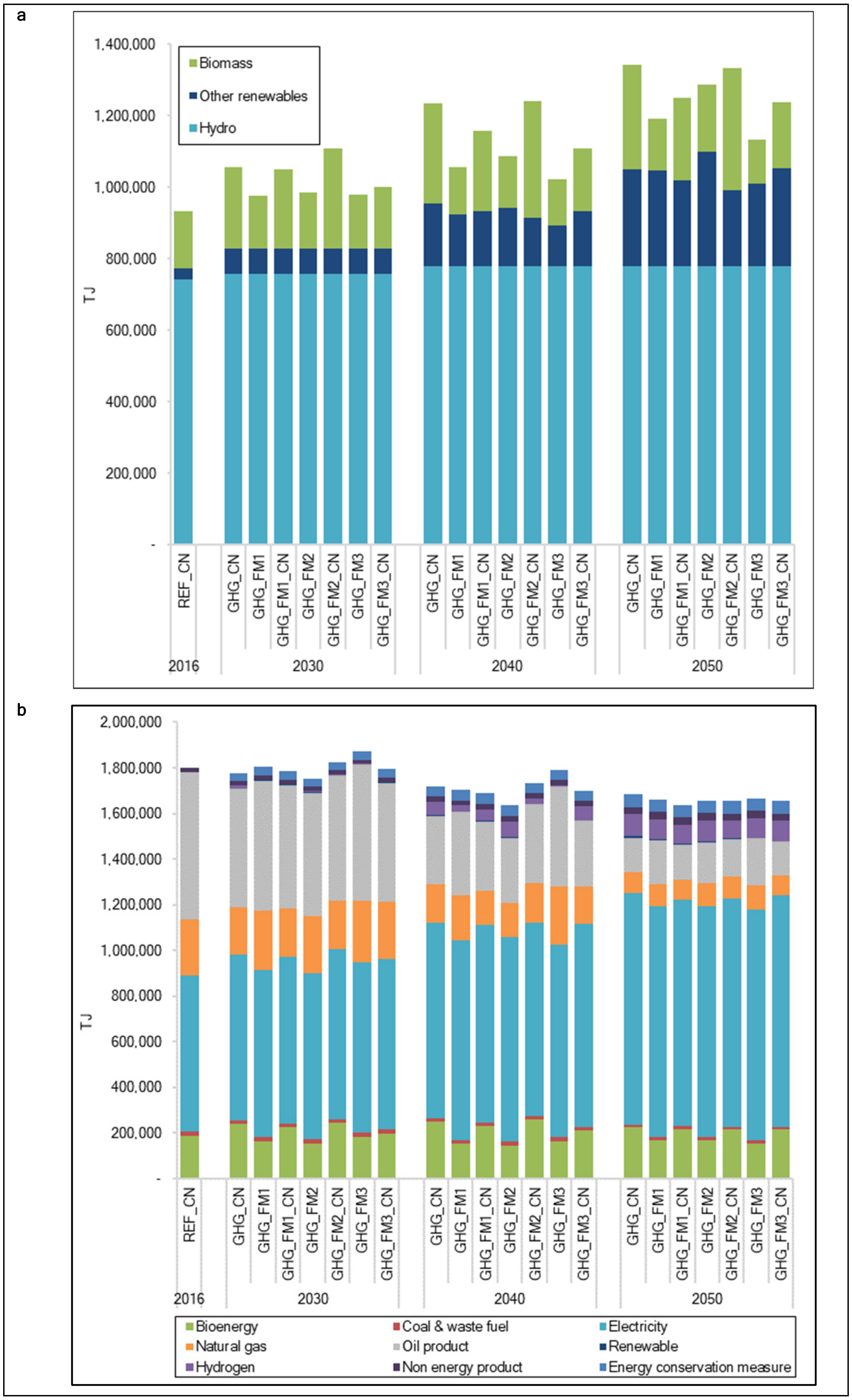

Figure 3.3 Energy production and consumption in Quebec, (a) primary energy production, (b) final energy consumption

Other energy sources such as crude oil, coal and natural gas are imported into Quebec. In 2050, total primary energy consumption reduces in GHG_FMx scenarios compared to respective REF_FMx scenarios (Figure A-II 4 in APPENDIX II). When compared to the corresponding reference scenarios, the portion of fossil fuel-based energy sources in GHG scenarios decreases. However, the decrease pace differs for each GHG scenario, resulting in a diverse rate of increase for renewable and bioenergy consumption. GHG_FM2, for example, has the highest increase in biomass and bioenergy consumption, leading to a lower reduction in total primary energy consumption than other GHG_FMx scenarios.

In 2050 (Figure 3.3(b)), total energy consumption in REF and GHG scenarios are around 2,080 EJ and 1,600 EJ, respectively. Bioenergy, coal and waste fuel, natural gas, and oil product usage in GHG scenarios decrease while the consumption of electricity and hydrogen form carbon-free sources increases compared to relative REF scenarios. The reduction in final energy consumption is due to the adoption of alternative and more efficient technologies that utilize electricity or hydrogen as energy sources. Hydrogen production and consumption are also illustrated in Figure A-II 5.

3.3.3 The carbon neutrality assumption leads to biased decision-making

Figure 3.4(a) displays total biomass output per forest management strategy between 2030 and 2050. The quantity of biomass produced in scenarios that use the same forest management strategy is the same, but the amount of unused residues or biomass left in the forest to decompose varies as a function of the constraints and assumptions used (Figure 3.4(b)). Decomposition emissions occur in future years as a result of residues left in the forest. Unused residues do not appear in scenarios following a carbon neutrality assumption because there is no penalty (biogenic emissions) for consuming the biomass. In 2030, GHG_FM2 and GHG_FM2_NO_BIOF are the only scenarios with unused residues. Because of the abundant available feedstock in FM2 compared to other forest management strategies, reference scenarios of FM2 leave extra residues in the forest in 2040. In addition to previous scenarios, unused residues occur in GHG_FM1_NO_BIOF in 2050. The biomass is distributed in accordance with the supply chain (Figure 3.1(a)) to meet the needs of primary and secondary industries, as well as bioenergy production.

The main difference between assuming or not assuming carbon neutrality is that emissions are higher in the short term without carbon neutrality. In 2050 (Figure 3.4(c)), taking biogenic emissions into account results in a reduction of around 25%, 34%, and 24% of bioenergy usage for GHG scenarios with FM1, FM2, and FM3, respectively. Except for biodiesel and black liquor, most bioenergies experience a reduction to meet the demand in the industrial sector. Solid biomass provides the required heat and electricity in industrial, commercial, and residential sectors or as a feedstock to produce hydrogen. In 2050, only GHG_FMx_CN scenarios use syngas. In GHG_FM1_CN, syngas consumption hits a peak of 3.7 PJ. The carbon neutrality assumption enables the model to use more biomass or bioenergy without being constrained by biogenic CO_2 emissions and as available sequestration in future years cannot balance biogenic CO_2 emissions, leading to biased decision-making.

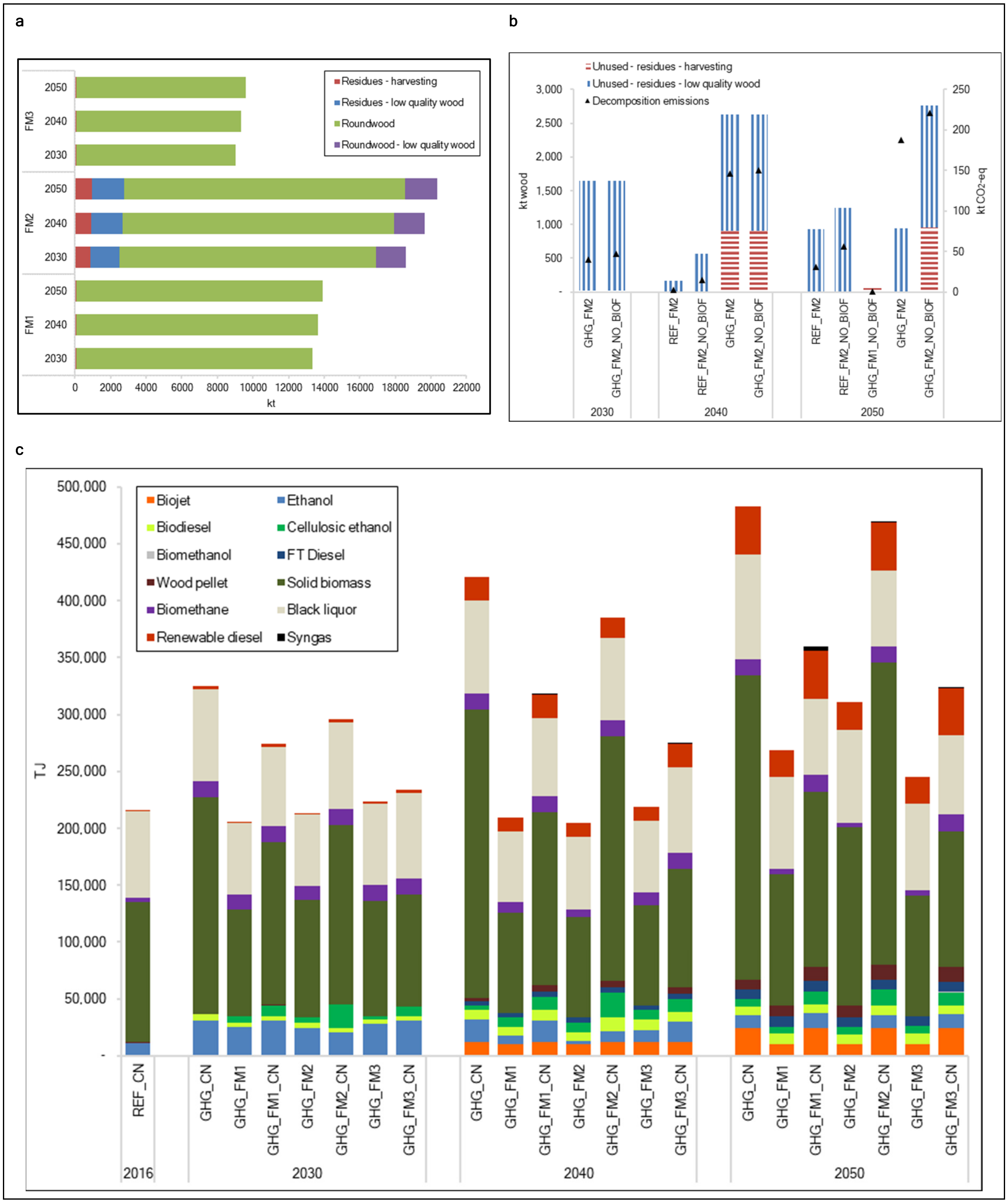
a
FM3
FM2
FM1
2050
2040
2030
Residues - harvesting
Residues - low quality wood
Roundwood
Roundwood - low quality wood
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
kt
b
Unused - residues - harvesting
Unused - residues - low quality wood
Decomposition emissions
kt wood
kt CO2-eq
3,000
2,500
2,000
1,500
1,000
500
-
250
200
150
100
50
0
GHG_FM2
GHG_FM2_NO_BIOF
REF_FM2
REF_FM2_NO_BIOF
GHG_FM1_NO_BIOF
2030
2040
2050
c
Biojet
Ethanol
Biodiesel
Cellulosic ethanol
Biomethanol
FT Diesel
Wood pellet
Solid biomass
Biomethane
Black liquor
Renewable diesel
Syngas
TJ
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
-
REF_CN
GHG_CN
GHG_FM1
GHG_FM1_CN
GHG_FM2
GHG_FM2_CN
GHG_FM3
GHG_FM3_CN
2016
2030
2040
2050

Figure 3.4 Alternative forest management strategies, (a) available feedstock in each forest management strategy, (b) unused forest residues and decomposition emissions, (c) impact of forest management strategies and carbon neutrality on bioenergy consumption

3.3.4 Importance of forest management strategy over BECCS

Figure A-II 7 in APPENDIX II shows different technologies (BIOF) and bioenergy mixes for each scenario. Including biogenic carbon affects the solution through choosing alternative BECCS and bioenergies (a detailed description is given in SI). For instance, syngas production through gasification is only activated in scenarios assuming carbon neutrality, and the amount of syngas produced varies depending on GHG emissions and uptakes associated with different forest management strategies.

Excluding BIOF (new forest-based bioenergy and BECCS) from scenarios reduces bioenergy consumption (see Figure A-II 8). In 2050, a reduction of around 8%, 20%, and less than 1% of bioenergy usage are projected for GHG scenarios with FM1, FM2, and FM3, respectively. Major reductions occur in wood pellet, solid wood and black liquor consumption. Bioenergy usage reduction for GHG_FM3_NO_BIOF is insignificant because the GHG_FM3 scenario does not use wood pellets as a source of energy in 2050. By discarding BIOF, the need for biomass reduces and the mass of unused residues increases (Figure 3.4(b); particularly for GHG_FM2_NO_BIOF in 2050). Of note though, the magnitude of the reduction can be different depending on the available biomass. Therefore, it is necessary to establish the most promising forest management strategy before investing in BECCS.

3.3.5 Forest sequestration decreases marginal abatement costs

Including biogenic carbon leads to a lower GHG abatement cost before 2040 for GHG_FM2 and before 2045 for GHG_FM1 and GHG_FM3 scenarios compared to GHG_FMx_CN scenarios (Figure 3.5(a)). This is due to the fact that biogenic CO_2 emissions for biomass and biofuel usage are taken into account, as well as to decreased forest sequestration capacity after

2045 (Figure 3.2(d)). In 2040, FM2 offers the lowest sequestration capacity and cannot offset biogenic CO_2 emissions in GHG_FM2 versus FM1 and FM3 forest management strategies in GHG_FM1 and GHG_FM3, respectively. When biogenic emissions are ignored, the marginal abatement cost of GHG_FMx_CN scenarios follows nearly identical trends. However, abundant available feedstocks in FM2, which can generate negative emissions via BECCS, result in lower marginal costs for GHG_FM2_CN than other carbon-neutral GHG scenarios. GHG_FM3 has slightly higher GHG mitigation costs than GHG_FM1 and GHG_FM2, due to a shortage of biomass supply and the need to import biomass at a high price.

Total bioenergy import (Figure 3.5(b)) decreases when considering biogenic carbon (GHG_FMx), while bioenergy export (Figure 3.5(c)) increases. Solid biomass is imported to cover the gap in each forest management strategy. Imported solid biomass, renewable diesel, and ethanol are expected to drop in 2050 GHG scenarios that take biogenic carbon into account. Biojet and biomethane become part of biofuels to be exported in 2050 GHG scenarios considering biogenic carbon. Wood pellet exports increase as well in comparison to GHG scenarios assuming carbon neutrality. Importing bioenergy involves no production emissions, which may be seen as burden shifting, and is the primary rationale for not activating some technologies capable of supplying these portions of bioenergy. It might also be attributed to a low import price. Therefore, a sensitivity analysis was performed on the import price of biofuel. Because all three GHG scenarios with a forest management strategy show a similar trade profile in 2050, GHG_FM3 in 2050 was chosen for this sensitivity analysis. A 50% increase in import/export prices yields the same bioenergy consumption profile, while a 50% reduction results in importing bioethanol (8565 TJ) and the same bioenergy consumption profile. Even though bioethanol is only used in the transportation sector in GHG_FM3, additional imported bioethanol is used for agriculture, commercial, and industrial purposes if the import price is reduced. The bioenergy trade profile is therefore not sensitive to an import/export price increase of 50% or less since it remains a competitive option, but a 50% price reduction would lead to higher bioethanol imports, which constitutes a potential burden shifting as the model does not account for imported fuel process emissions.

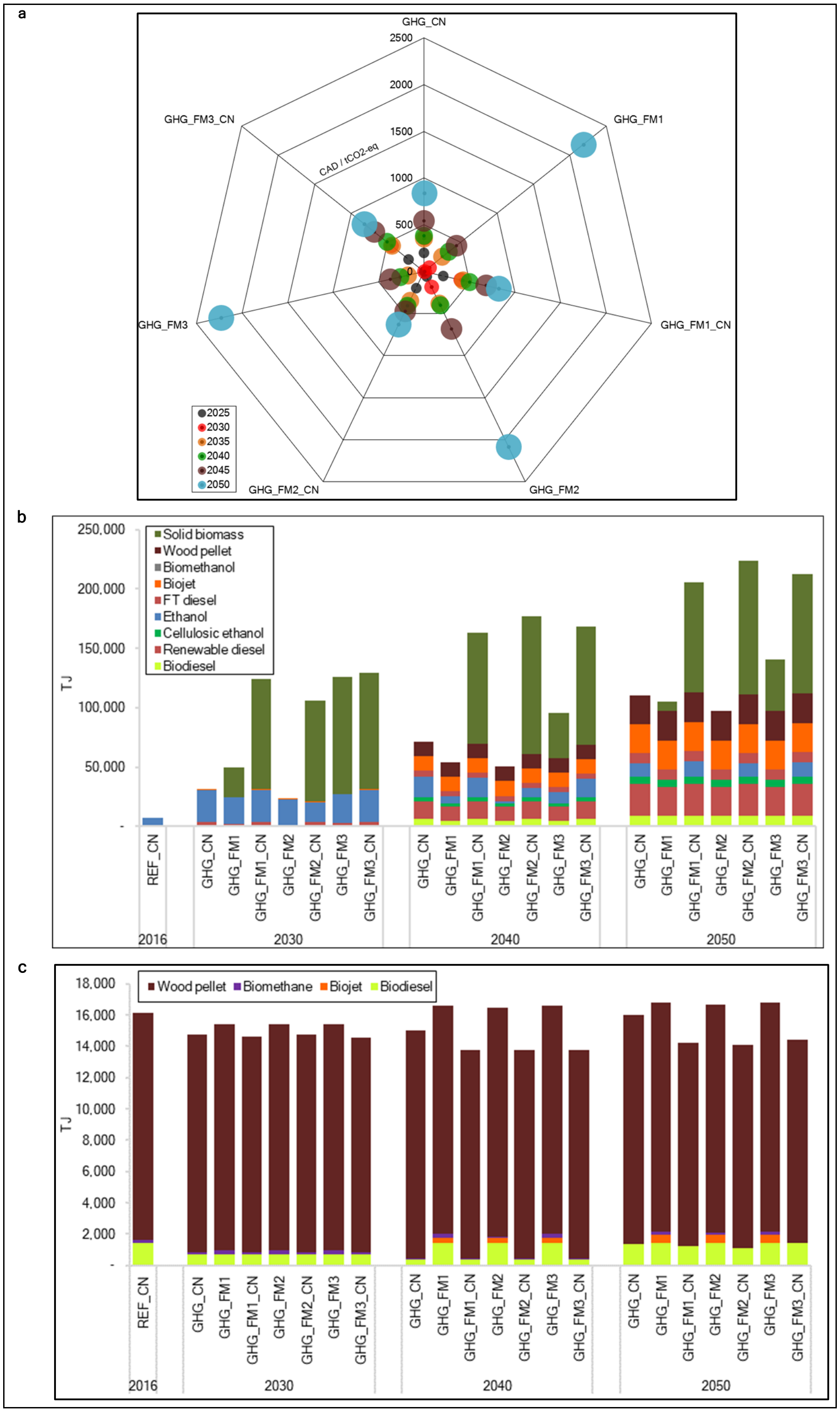
a
GHG_CN
2500
2000
1500
1000
500
0
CAD / tCO2-eq
GHG_FM1
GHG_FM1_CN
GHG_FM2
GHG_FM2_CN
GHG_FM3
GHG_FM3_CN
2025
2030
2035
2040
2045
2050
b
250,000
200,000
150,000
100,000
50,000
-
TJ
Solid biomass
Wood pellet
Biomethanol
Biojet
FT diesel
Ethanol
Cellulosic ethanol
Renewable diesel
Biodiesel
REF_CN
GHG_CN
GHG_FM1
GHG_FM1_CN
GHG_FM2
GHG_FM2_CN
GHG_FM3
GHG_FM3_CN
2016
2030
2040
2050
c
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
TJ
Wood pellet
Biomethane
Biojet
Biodiesel
REF_CN
GHG_CN
GHG_FM1
GHG_FM1_CN
GHG_FM2
GHG_FM2_CN
GHG_FM3
GHG_FM3_CN
2016
2030
2040
2050

Figure 3.5 (a) Marginal mitigation costs (CAD per tCO_2-eq) for different scenarios, (b) bioenergy import and (c) bioenergy export in Quebec

3.4 Discussion

This study shows that the assumption of carbon neutrality could lead to biased decision-making when analyzing global and national roadmaps to net-zero CO_2 emissions by 2050. We used the province of Quebec as a case study to demonstrate how the assumption of carbon neutrality leads to a biased decision. After 100 years, around 60% of the carbon emitted from the combustion of residual biomass is removed from the atmosphere and returned to the biosphere (Adetona et Layzell, 2023). Assuming carbon neutrality in GHG calculations by ignoring biogenic CO_2 emissions can lead to underestimation of the true emissions impact. This is because it could take more than 100 years for the emitted carbon to be fully removed from the atmosphere. Hence, if biogenic CO_2 emissions are included in GHG calculations, the emissions impact of biomass consumption is higher in the short term compared to when they are ignored. However, over the long term, both approaches result in equal emissions impact. Regions with lower forest coverage or sequestration potential risk more biased decisions since available forest sequestration cannot sink biogenic emissions in the short term. They will not produce forest bioenergy because they do not have available resources, but they could rely on imports. Importing bioenergy from regions that do not account for carbon loss associated with biomass harvest may exacerbate the situation for these regions by increasing biogenic emissions without the ability to sink them in the short term. In 2021, 44 countries submitted their national inventory reports (NIRs) to the UNFCCC (UNFCCC, 2021). These reports are usually generated using a carbon budget model. TIMES is used by over 80 institutions in 63 countries (Bahn et Vaillancourt, 2020 ; IEA-ETSAP, 2023). The proposed integrated approach could be adopted in any of the countries using a TIMES approach together with a carbon budget model. Additionally, the detailed approach used for modeling forest-based bioenergy and BECCS may be easily extended to different regional contexts by updating related costs.

Choosing climate targets of 37.5% by 2030 and net-zero by 2050 based on the 1990 level (with biogenic carbon neutrality) for scenarios considering biogenic carbon (GHG_FMx, GHG_FMx_NO_BIOF) might be debatable. Biogenic carbon must be included when computing 1990 GHG emission levels by adding biogenic CO_2 emissions of bioenergy consumption and forest net emission. To address this issue, we added forest sequestration from each forest management strategy at the start of the time horizon and biogenic emissions from the related reference scenario to the 1990 GHG emission level.

A circular economy is envisioned for HWPs usage in the future. It implies that at the end of their lifetime, HWPs are transformed to another product (no biogenic emission) or energy (biogenic emission) rather than ending up in a landfill. To consider HWPs decomposition emissions over time, one would need to use a modeling framework for HWPs, which is beyond the scope of this paper. This study does not take into account either the substitution effect of using HWPs instead of non-wood materials such as cement and steel. Future research could include HWPs and substituted materials in the model.

One can question Quebec's high forest sequestration compared to Canada's projected LULUCF of -11 Mt CO_2-eq in 2030 (Environment and Climate Change Canada, 2022). This is because forest sequestration in our study does not consider biomass combustion emissions. It shows forest net emissions, extraction, transport, and manufacturing emissions, and residue decomposition. NATEM accounts for biomass combustion emissions by using biomass as a source of energy. Almost half of the produced HWPs returns to the model to be used as a source of energy and the other half is assumed to be sequestered permanently. Furthermore, while some regions of Canada have a high capacity for carbon sequestration, others are net emitters (Smyth *et al.*, 2017). This research only considers forest sequestration as a component of LULUCF, and excludes cropland, grassland, wetlands, and settlements, which are beyond the scope of this study. Other LULUCF as potential CDR strategies could be added to the energy system model.

CDR strategies through measures in agriculture, forestry and other land use could be sustained for decades, but not for very long because these sinks will eventually saturate (Riahi *et al.*, 2022 ; Lecocq *et al.*, 2022). This is observed in this analysis, as forest sequestration decreases at the end of the time horizon. The current setup of NATEM-Quebec does incentivize to delay biogenic emissions after 2050, and therefore, any results may turn out to be suboptimal as soon as post-2050 targets are defined. We acknowledge this as a limitation of this study, which will be addressed in a forthcoming study. The data from the previous decades used to calculate the disturbance rate in Canadian forests might not accurately represent the future disturbance rate as recent years have shown a significant increase (NRCan, 2022). Further research is recommended to examine increased levels of disturbances, particularly in a changing climate projected to significantly impact forest disturbance patterns (Seidl *et al.*, 2017). The current setup of NATEM-Quebec allows leaving additional residues in the forest without considering the potential for increased fire risk. We acknowledge this limitation of the developed integrated approach, which will be addressed in a forthcoming study by incorporating feedback from NATEM-Quebec into the CBM-CFS3 model. Besides a business-as-usual forest management scenario, only two strategies were selected for this study to reflect intensification and conservation. Since different forest management strategies lead to different outcomes, as observed in this article, other forest management strategies and terrestrial sequestration approaches could be integrated into the energy system model to obtain a more comprehensive result. Integrated assessment models (IAMs) could also help to identify efficient pathways for future work, as they model cost-effective strategies for achieving specific climate targets while taking into account intersectoral competition for biomass and land carbon balances related to land use and biomass provision.

3.5 Conclusion

Taking forest sequestration into account can help alleviate the decarbonization effort by flattening GHG trajectories and allowing policymakers to use available forest sequestration for difficult-to-decarbonize sectors. We recommend including biogenic CO_2 emissions in NDC since excluding them affects the solution. It can also affect the solution through choosing alternative BECCS. It is necessary to identify the most promising forest management strategy before investing in BECCS because the model employs various methods of biomass utilization based on available biomass and the sequestration potential. When available, forest sequestration cannot offset biogenic CO_2 emissions, and GHG abatement costs increase exponentially. Including biogenic emissions reduces biomass and bioenergy usage in GHG scenarios. Therefore, assuming biogenic carbon neutrality may result in biased decision-making because it allows the model to use more biomass without being constrained by biogenic CO_2 emissions. We may not be able to invest in BECCS, DAC or other negative emission technologies in the short-term, but we can shift to forest management strategies that carry a lower cost than other NETs to make it easier to limit warming to 2°C after 2030 and achieve net-zero emissions by 2050. The goal of net-zero emissions by 2050 can be achieved by improving energy efficiency using technological alternatives, decarbonization of electricity generation, massive electrification, and deployment of negative emission technologies such as forest management strategies with high forest sequestration. We believe more stringent emission reduction targets could be adopted before 2030. Hence, we recommend that the Canadian forest sector be fully integrated into NATEM in order to allow a successful planning of the next steps for clean air and a strong economy. It is also recommended that countries with a significant forest industry include a detailed forest sector in a bottom-up energy model.

CHAPTER 4

THE ROLE OF HYDROGEN IN A NET-ZERO EMISSION ECONOMY UNDER ALTERNATIVE POLICY SCENARIOS

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Abstract

Low emission and green hydrogen as a carbon-free energy carrier has attracted worldwide attention in decarbonizing the energy system and meeting the Paris agreement target of limiting warming to 2°C or below. This study investigates the contribution of different hydrogen pathways to the energy transition and sheds light on adopting different decarbonization scenarios for Quebec, Canada, while including biogenic emissions from forest-based biomass consumption. We assess various alternative policy scenarios using a TIMES model for North America (NATEM), a bottom-up techno-economic approach. This study examines the role of various hydrogen pathways in Quebec's energy transition by considering different net-zero policy scenarios and an additional set of "green" scenarios, which prohibit the use of fossil fuel-based hydrogen. The results show that varying the penetration of hydrogen provides a key trade-off between reliance on direct air capture, reliance on carbon storage, reliance on wind and solar buildout, the inter-sector allocation of residual emissions, and the overall cost of achieving emission targets. In particular, the use of hydrogen in the industrial sector, a sector known to be difficult to decarbonize, reduces industrial emissions and reliance on direct air capture (DAC). Clustering industrial plants to use captured CO_2 as a feedstock for synthetic fuel production may not reduce industrial GHG emissions by 2050, but it offers the opportunity to use captured CO_2 instead of sequestering it in deep saline aquifers. Even though increasing industrial green hydrogen penetration increases marginal GHG abatement costs in the green net-zero scenario by 2050, it further minimizes industrial GHG emissions and the need for DAC among all net-zero scenarios by 2050. Hydrogen plays a significant role in achieving ambitious net-zero emission target, especially where electrification is not feasible, or electricity storage is required.

Keywords: Net-zero emission; energy system decarbonization; TIMES model; hydrogen

4.1 Introduction

Hydrogen is increasingly being considered in different countries' roadmaps to meet the Paris agreement's target of limiting warming to 2°C or less. These include the United States (FCHEA, 2021), the United Kingdom (Department for Business E& IS, 2021), the European Union (European Commission, 2020), Japan (METI, 2019), Australia (COAG Energy Council, 2019), and Canada (NRCan, 2020). Global hydrogen production in 2021 reached 94 million tonnes, primarily through natural gas reforming without carbon capture, utilization, and storage (CCUS), releasing more than 900 Mt CO_2 into the atmosphere (IEA, 2022). Less than 1% of this hydrogen was produced using fossil fuels with CCUS or electricity and the rest was produced via coal gasification, oil, and as a by-product of naphtha reforming at refineries.

The hydrogen produced by natural gas reforming is known as grey hydrogen. Combining this process with CCUS results in lower process emissions and is called blue hydrogen. Green hydrogen is produced using renewable electricity in electrolyzers (Razi et Dincer, 2022). Gasification of biomass could also be considered as another method for producing green hydrogen. Combining biomass gasification with CCS (BECCS) results in negative emissions (if the biomass source is carbon neutral) (NASEM, 2019 ; Capurso *et al.*, 2022). Blue and green hydrogen have attracted attention, primarily because of the ability to minimize reliance on fossil fuels, improve energy security, and decarbonize the energy system (IEA, 2022). Biomass-based hydrogen generation, however, faces technological and economic challenges stemming from low efficiency and impurity issues (Hamedani Rajabi *et al.*, 2016).

Several studies have assessed the role of hydrogen in climate change mitigation. Bauer et al. (2022) assessed the climate impact of blue hydrogen using a process simulation coupled with a life cycle assessment. Results showed that blue hydrogen could have a range of climate impacts depending on the rate of CH_4 emissions in natural gas production, the ratio of CO_2 captured during hydrogen production, and the metric used to quantify global warming. Combining a high CO_2 capture ratio with a low CH_4 emission rate could make blue hydrogen suitable for economies moving toward zero emissions, while showing climate change impacts comparable to the upper range of electrolysis using renewable electricity. Hermesmann and Müller (2022) also analyzed environmental impacts of different hydrogen production processes using a life cycle approach. They showed that upstream flows such as power generation and natural gas production greatly influence the environmental impacts of hydrogen production technologies. However, these studies lack techno-economic modeling, preventing a clear understanding of potential penetration of hydrogen in the energy system.

Net zero studies based on Energy-Environment-Economy (E3) models provide additional insight on which combinations of end-use technologies provide economically optimal paths towards full decarbonization, including hydrogen technologies but also competing energy efficiency, bioenergy, carbon capture and direct electrification technologies. Many research projects look at hydrogen more specifically, using E3 models in the TIMES (Loulou, Lehtilä, *et al.*, 2016) family and following a carbon neutrality assumption. For instance, Blanco et al. (2018) used the JRC-EU-TIMES model to assess the role of hydrogen and synthetic liquid fuels in the European GHG reduction strategy. The results show that factors with the largest impact are the GHG reduction target, biomass, and geologic CO_2 sequestration availabilities.

Espegren et al., (2021) assessed the role of hydrogen in Norway's energy transition using three analytical perspectives, including an energy systems perspective with a TIMES model. Renewable energy and hydrogen were identified as essential components in decarbonizing Norwegian transportation and industrial sectors. Yang et al. (2022) used a TIMES-based energy system optimization model (China-MAPLE) to investigate the role of hydrogen in difficult-to-decarbonize sectors of heavy industries and heavy-duty transportation in China. According to the findings, clean hydrogen can be used as an energy carrier and feedstock in decarbonizing heavy industry, as well as a fuel for up to half of the Chinese transportation sector. Using TIAM-ECN, a TIMES-based model, van der Zwaan et al. (2021) investigated the export of electricity and hydrogen from North Africa to Europe. They found solar power could be produced in significant quantities of renewable electricityin North Africa and to be economically transmitted to Europe, or it could be converted to hydrogen via electrolysis and transported to the Eurozone via pipeline. In the Net-Zero America study (Larson *et al.*, 2021), which relies on the EnergyPATHWAYS and RIO models, hydrogen plays a significant role in seasonally balancing the grid by the late 2040s, through intermittent electrolysis, intermittent hydrogen steam boilers (alternating with electrical ones), and hydrogen use in natural gas power plants, across all net zero scenarios. The largest part of hydrogen, however, is produced via biomass gasification with CO_2 capture and storage (BECCS) in most net zero scenarios. Electrofuel production is a major consumer of hydrogen only in scenarios restricting direct electrification or CO_2 storage. The International Energy Agency Net Zero by 2050 Roadmap (IEA, 2021), using the WEM and ETP models, finds comparable uses of hydrogen, with more emphasis on direct use of hydrogen and ammonia as transportation fuels, while biomass is directed more towards solid fuel applications. BECCS is entirely absent as a source of hydrogen; it is not specified whether this is because the technology is absent from the model, because the optimizer has chosen not to use it, or because the different geographical and policy aspects of the model penalize it. In another example, a study done for Quebec (Dunsky et ESMIA, 2021), using a variant of the model used in the present study (NATEM), concludes in a somewhat limited use of hydrogen in the context of the hydroelectricity-rich province. It is produced entirely using BECCS, serves primarily the industrial and transportation sectors, and is presented more as an economic source of negative emissions than as an important replacement fuel. Interestingly, two scenarios that respectively allow and deny negative emissions, but are otherwise nearly identical in their input assumptions, show a major shift as to whether biomass should optimally be allocated to produce hydrogen or liquid fuels. Overall, there is a significant disagreement between modelling-based studies about the extent to which hydrogen is necessary or useful to fully decarbonize at the lowest possible cost, and about the relevance of negative emissions provided by BECCS in that context. The development of E3 models is ongoing, which contributes to an improved understanding of the efficient allocation of scarce renewable resources such as forest residue.

The relevant literature has been extensively researched, and numerous papers, such as those mentioned above, have investigated the role of hydrogen towards a net-zero economy using E3 models and TIMES in particular. However, this is the first regional (Quebec, Canada) techno-economic study of different hydrogen pathways that considers GHG emissions and uptakes associated with forest management and BECCS, as well as biogenic CO_2 flows. This allows to obtain more explicit results on the contribution of different emerging hydrogen technologies, in particular biomass-based (green) hydrogen, as the assumption of carbon neutrality for forest biomass could lead to accounting errors and biased decision-making, for example by over-allocating forest residue to BECCS hydrogen production, when it could instead be optimal to leave them in the forest (Kouchaki-Penchah, Bahn, Vaillancourt, *et al.*, 2023 ; Berndes *et al.*, 2016).

This paper is structured as follows. The undertaken modelling approach is presented in section 2, along with the available hydrogen pathways and alternative policy scenarios. Section 3 reveals the key findings while providing further details in the supplementary information. Section 4 discusses the outcomes of this study, and Section 5 provides a summary and conclusion.

4.2 Methodological approach

4.2.1 TIMES modeling approach

The TIMES model is an upgraded version of the MARKAL model combined with the EFOM method, which was developed under the IEA ETSAP program (Loulou, Goldstein, Kanudia, Lettila et Remme, 2016). This type of bottom-up model is useful for representing energy systems in a specific region and is particularly effective for depicting systems that are using new or emerging energy sources (Bahn, 2018). In this model, a detailed reference energy system (RES) is established to illustrate various energy carriers and technologies that span from primary energy production to final energy consumption. The demands for energy services are externally introduced to facilitate the use of a diverse range of end-use technologies that rely on different forms of final energy (Bahn et Vaillancourt, 2020). The TIMES model is designed as a linear programming model that simultaneously determines technology investment and operation, primary energy supply, and energy trade decisions for each region, while minimizing total surplus loss and meeting final energy demands (Loulou, Goldstein, Kanudia, Lettila et Remme, 2016). The model's decision variables represent choices that must be made endogenously, such as the selection of specific energy technologies and commodities. Model constraints capture the physical and logical interactions that must be considered to accurately model the entire energy sector (Loulou, Goldstein, Kanudia, Lettila et Remme, 2016). For a complete documentation of the TIMES model, please refer to (Loulou, Goldstein, Kanudia, Lettila et Uwe Remme, 2016).

4.2.2 NATEM model

The North American TIMES Energy Model (NATEM) models the Canadian energy sector using a TIMES approach. NATEM encompasses 70 different end-use demands for energy services across various sectors, such as agriculture, commercial, industrial, residential, and transportation (Vaillancourt *et al.*, 2017). For this study, a comprehensive depiction of

Quebec's energy system has been derived from NATEM. The sub-model, known as NATEM-Quebec, covers the entire province and utilizes data that is disaggregated by sub-regions. NATEM-Quebec is calibrated to a 2016 base year and has a time horizon of 2060, which is divided into 9 periods and 16 annual time slices. All costs are expressed in 2016 Canadian dollars and a global yearly discount rate of 5% is applied (Vaillancourt, Bahn et Levasseur, 2019). More than 4000 different energy technologies, 800 commodities, and 700 user constraints are included in NATEM-Quebec. This version of the model also includes different forest-based bioenergy pathways and accounts for forest carbon sequestration and biogenic emissions associated with forest biomass and bioenergy consumption, see (Kouchaki-Penchah, Bahn, Vaillancourt, *et al.*, 2023 ; Kouchaki-Penchah *et al.*, 2022). The VEDA2.0 model management system (KanORS-EMR, 2022) obtains input from NATEM-Quebec, which contains data and assumptions. Subsequently, the TIMES code is executed in the GAMS environment (GAMS, 2023), generating a linear programming problem comprising of over 300,000 equations and approximately 400,000 variables. The linear programme is optimized using the CPLEX solver (KanORS-EMR, 2022).

4.2.3 Hydrogen production pathways

NATEM includes a variety of hydrogen and ammonia production technologies, with and without CCS, as well as a detailed distribution network, storage technologies, and a wide range of options for use in each sector of the energy system.

4.2.3.1 Steam reforming (SR)

Steam reforming of hydrocarbons stands as the leading industrial process for hydrogen and synthesis gases production. The prevalent used raw materials are natural gas and lighter hydrocarbons, methanol, and other oxygenated hydrocarbons. In this process, synthetic gas that contains mainly carbon monoxide and hydrogen is first produced. Subsequently, via the water–gas shift reaction, carbon monoxide is converted to carbon dioxide and additional hydrogen. For instance, overall, each molecule of methane is converted to a molecule of carbon dioxide and 4 molecules of hydrogen by 2 molecules of water (steam). This reaction is highly endothermic, and a large amount of high-temperature (800-1000 ºC) heat is required (Farnell, 2016). Conventional industrial reformers consist of numerous fixed-bed tubes that contain nickel catalyst particles and are housed within gas-fired furnaces. However, these industrial fixed-bed steam reformers exhibit various disadvantages that significantly impact their operation and performance. These drawbacks include thermodynamic equilibrium limitations, carbon formation on the catalyst, a large temperature gradient, and low heat transfer rates, which seriously affect their operation and performance. Fluidized bed reactors present viable alternatives for conducting reforming reactions. By utilizing a solid catalyst as a heat carrier within the fluidized bed reformer, a more uniform temperature distribution can be achieved, effectively addressing the issue of hot spots commonly observed in fixed bed reactors. Fluidized bed reactors offer significant advantages such as enhanced heat transfer, improved catalyst bed uniformity, and elimination of diffusion limitations within the catalyst. Additionally, these reactors enable the continuous introduction of fresh catalyst into the reformer and facilitate the catalyst regeneration process (Bashiri *et al.*, 2014). Hydrogen purification in hydrogen plants is achieved using the pressure swing adsorption system. This system has the capability to generate hydrogen with a purity of up to 99.999%, while achieving a recovery of 70−95% (Megia *et al.*, 2021).

4.2.3.2 Partial oxidation (POx)

POx involves the combustion of a hydrocarbon fuel such as natural gas with a limited supply of oxygen to produce a syngas mixture, consisting of carbon monoxide, hydrogen, and other trace gases. The syngas mixture produced by POx typically has a higher concentration of carbon monoxide that can be further processed to produce more hydrogen gas through a variety of methods, such as water-gas shift reactions. POx process is typically operated a about 950 ºC for methane and light hydrocarbon in the presence of catalyst and about 1300 ºC for methane and heavy oil and coal without using any catalyst which can lead to more efficient conversion of the feedstock to hydrogen gas (Steinberg et Cheng, 1989). Although it is an expensive process, mainly due to the desulphurization and oxygen recirculation step, it remains the most promising technology for producing hydrogen from heavier fossil hydrocarbon such as heavy oil residues and coal.

4.2.3.3 Auto thermal reforming (ATR)

ATR combines the processes of POx and steam reforming in a single reactor, using a controlled mixture of oxygen, steam, and hydrocarbon fuel to produce a syngas mixture. More precisely, the heat required by steam reforming comes from the partial oxidation of the hydrocarbon fuel in the ATR process. While ATR requires a higher amount of oxygen supply than POx, in order to maintain the desired reaction conditions, it typically operates at lower temperatures and pressures than POx. The ATR process is yet to become commercially available on a large scale (Ji et Wang, 2021).

4.2.3.4 Pyrolysis

Pyrolysis involves the thermal or thermocatalytic decomposition of a wide range of feedstocks such as liquid hydrocarbons under specific conditions and in an oxygen-free environment to produce hydrogen . Pyrolysis often does not require CO_2 removal steps; therefore, its capital cost can be lower compared to SMR and POx technologies leading to a lower hydrogen production cost. The low partial pressure of hydrogen in the gas mixture produced is a significant drawback of this technology, as it poses a challenge to the purification steps (Muradov, 2001).

4.2.3.5 Gasification

Gasification is a promising technology for the utilization of various feedstocks, particularly biomass, to produce energy and added-value products such as hydrogen (Bashiri, Ashrafi et

Navarri, 2021). Biomass gasification is a thermochemical process that converts biomass into a gaseous fuel called syngas, using a gasification medium such as air, oxygen, and/or steam. The process occurs at temperatures ranging from 500 to 1400 °C and operating pressures that can range from atmospheric to 33 bar, depending on the plant scale and final application of the produced syngas. The types of reactors used for biomass gasification are classified according to the flow and velocity of the gasifying agent, with fixed bed, fluidized bed, and indirect gasifiers being the most common. The syngas produced by biomass gasification contains a mixture of primary components, including carbon monoxide (CO), hydrogen (H_2), carbon dixide (CO_2), methane (CH_4) and water vapor (H_2O), as well as secondary components such as tar (aromatic hydrocarbon species), particulate matter, sulphur compounds, hydrochloric acid, ammonia, hydrogen cyanide, isocyanic acid, nitrogenous compounds, and alkali metal species. The characteristics of the feedstock, the design of the gasifier, the choice of gasifying agents, and the specific operating conditions of the gasification process collectively determine the composition of the resulting syngas, including the presence and levels of impurities. To separate hydrogen in high concentration from other components in the syngas mixture, the produced syngas must undergo multiple conversion and purification steps. The purification of syngas presents a major challenge for the commercial-scale implementation of the gasification process, mainly due to the high capital and operating costs involved (Bashiri *et al.*, 2018 ; Nikolaidis et Poullikkas, 2017).

4.2.3.6 Water electrolysis

Hydrogen production by electrolysis of water, which requires electrical energy, is a well-established endothermic process. Although it is currently used for small-scale industrial hydrogen production, it has great potential for future large-scale hydrogen production, given the increasing availability of renewable energy sources (IRENA, 2023). The process of water electrolysis relies on an electrolyzer, which can be categorized into different types based on the electrolytes employed. The most common types of electrolyzers used for water electrolysis are alkaline electrolysis (AEL), polymer electrolyte membrane (PEM) electrolysis, alkaline anion exchange membrane (AEM) electrolysis, and solid oxide electrolysis (SOEL) (Nazir *et al.*, 2020).

AEL and PEM electrolysis are typically carried out at temperatures ranging from 50 to 90 ºC (Carmo *et al.*, 2013). These two electrolysis technologies are well-established and widely implemented in commercial hydrogen production plants. Compared to AEL, PEM electrolysis has several advantages such as a more compact system design and higher current density. While PEM electrolysis is more energy efficient than AEL, it requires the use of noble metal electrodes such as iridium, ruthenium, and platinum, whereas AEL can utilize less expensive nickel-based or iron-based electrodes. AEM electrolysis employs a low-concentration alkaline solution or water as its electrolyte, in contrast to the high-concentration KOH utilized in AEL. Although still in its early stages of development, AEM shares a similar principle to PEM electrolysis, with the main difference being the charge carriers. Additionally, the lower equipment cost of AEM may contribute to its potential for higher commercial value.

SOEL operates at a higher temperature range of 500 to 1000 ºC and utilizes both electricity and heat to drive the water decomposition reaction, resulting in higher energy efficiency compared to AEL and PEM electrolysis. While SOEL is not yet reached commercial availability for hydrogen production, its inverse process capability (solid oxide fuel cells) and the projected low cost (by 2050) indicate promising prospects for its future potential (Ji et Wang, 2021).

4.2.4 Alternative policy scenarios

This study considers six main scenarios to examine the role of different hydrogen pathways in Quebec's energy transition. Because the question of whether natural gas is a useful transitional energy (and hydrogen) source is often debated, an additional set of so-called "green" scenarios is based on the main scenarios but prohibits any use of fossil fuel-based hydrogen after 2025.

1. a reference scenario (REF), with existing governmental policies and no net-zero emissions target;
2. a GHG reduction scenario (NZ_2050), with reduction targets of 37.5% by 2030 (from 1990 levels) and net-zero by 2050;
3. a GHG reduction scenario (NZ_2050_IND) similar to NZ_2050 but including a moderate industrial hydrogen penetration of 25% in 2025 and more substantial penetration of 70% in 2050 to highlight the potential role of hydrogen in decarbonizing industry. The term "penetration of industrial hydrogen" refers to the proportion of steam generated using hydrogen, expressed as a ratio of the total amount of steam generated by the industry. The industrial sector is often recognized as a hard-to-decarbonize sector, as highlighted in our previous study (Kouchaki-Penchah et al., 2023);
4. a GHG reduction scenario (NZ_2050_CCU) similar to NZ_2050 but including a policy of expanding industrial CCU by disabling the aquifer sequestration option for captured industrial CO_2 emissions through CCS. This scenario assesses the potential role of CCU technologies, which use hydrogen as a feedstock, in decarbonizing the industrial sector, as opposed to technologies that would use hydrogen as a heat carrier;
5. a GHG reduction scenario (NZ_2040) with reduction targets of 37.5% by 2030 (from 1990 levels) and net-zero by 2040, to see the effect of this stringent target on the energy system and hydrogen technologies;

6. a GHG reduction scenario (NZ_2060) with reduction targets of 37.5% by 2030 (from 1990 levels) and net-zero by 2060, to see the effect of postponing the net-zero GHG reduction target on the energy system and hydrogen technologies.
7. NZ_2050_green
8. NZ_2050_IND_green
9. NZ_2050_CCU_green
10. NZ_2040_green
11. NZ_2060_green

Demand for energy services is projected to 2050 from 2016 in all scenarios using socio-economic assumptions (GDP, GDP per capita, population growth) from the Trottier Energy Futures Project (TEFP, 2016). In addition, all these scenarios take into account current government energy and climate policies (Government of Canada, 2010 ; Government of Quebec, 2012 ; Ministère des Transports du Québec, 2015 ; NHTSA, 2011). Biogenic CO_2 emissions were included in the scenarios considered, as the assumption of biogenic carbon neutrality could lead to biased decision-making (Kouchaki-Penchah, Bahn, Vaillancourt, *et al.*, 2023). The merit order of hydrogen technologies was constructed using the model results by calculating the unit variable costs of the technologies and ranking them accordingly. The unit variable costs describe the total variable costs in time T for each hydrogen technology per hydrogen output of the technology. Total variable costs were calculated by summing up the purchase costs of all inputs and emissions, the activity costs, and the flow costs.

4.3 Result analysis

4.3.1 GHG emissions

Total GHG emissions of the net-zero and reference case scenarios are depicted in Figure 4.1. The NZ_2040 scenario is forced to get to net zero emissions in 2040, while the NZ_2050 and NZ_2060 scenarios are emitting about 22 Mt CO_2-eq and 26 Mt CO_2-eq in 2040, respectively. In 2040, 15.8 Mt CO_2-eq of the reduction of GHGs in NZ_2040 compared to NZ_2050 are achieved by GHG reductions in different sectors, particularly the transport and industrial sectors, while the remaining 6.2 Mt CO_2-eq is achieved using DAC (Figure 4.2). In 2050, NZ_2050 requires 7.9 Mt CO_2-eq to be removed by DAC, while NZ_2050_IND, NZ_2050_CCU, NZ_2040, and NZ_2060 require 5.5, 7.3, 6.4, and 2 Mt CO_2-eq respectively. Thus, adding a model constraint to increase hydrogen uptake tends to decrease DAC dependency. Similarly, CCU expansion in NZ_2050_CCU scenario, a higher GHG reduction target in NZ_2040 scenario, and postponing GHG reduction target in NZ_2060 scenario, all contribute to reducing the dependency on DAC when compared to NZ_2050. Increasing industrial hydrogen penetration leads to lower industrial GHG emissions. CCU expansion also results in higher hydrogen consumption and accordingly lower GHG emissions.

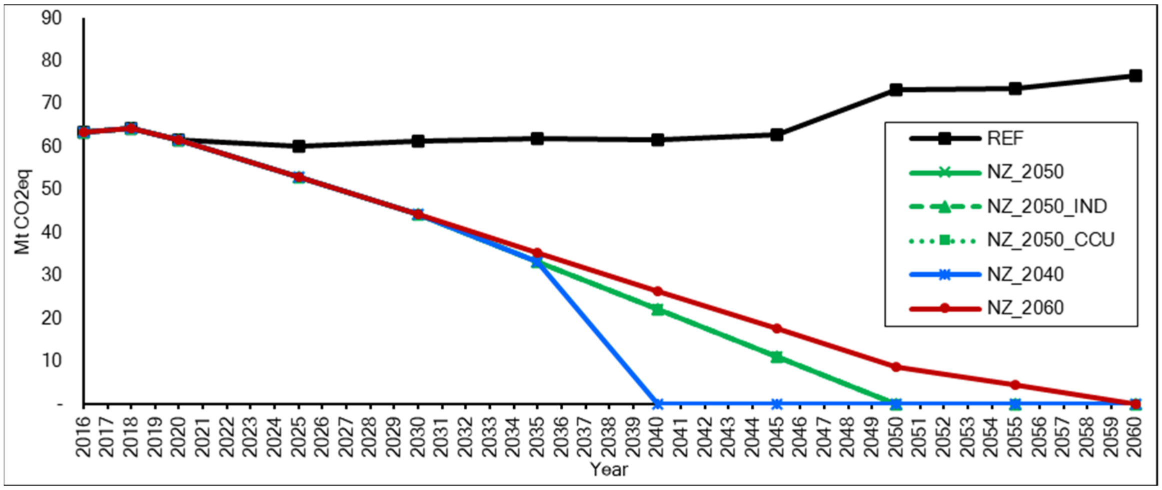


Figure 4.1 Total net GHG emissions of all scenarios

In 2050, total net industrial GHG emissions of NZ_2050 are about 5 Mt CO_2-eq, whereas they are around 3.1 Mt CO_2-eq for NZ_2050_IND and 5.85 Mt CO_2-eq for NZ_2050_CCU (Fig 2). The use of hydrogen as a carbon-free energy carrier helped to reduce GHG emissions from the industrial sector in NZ_2050_IND, while a policy of expanding CCUs in NZ_2050_CCU kept industrial GHG emissions relatively high, so that available industrial CO_2 could be converted into synthetic fuels, which could then be used as alternative energy sources in the subsequent transport and industrial sectors. Although the industrial emissions decrease in NZ_2050_CCU compared to NZ_2050 in years after net-zero target.

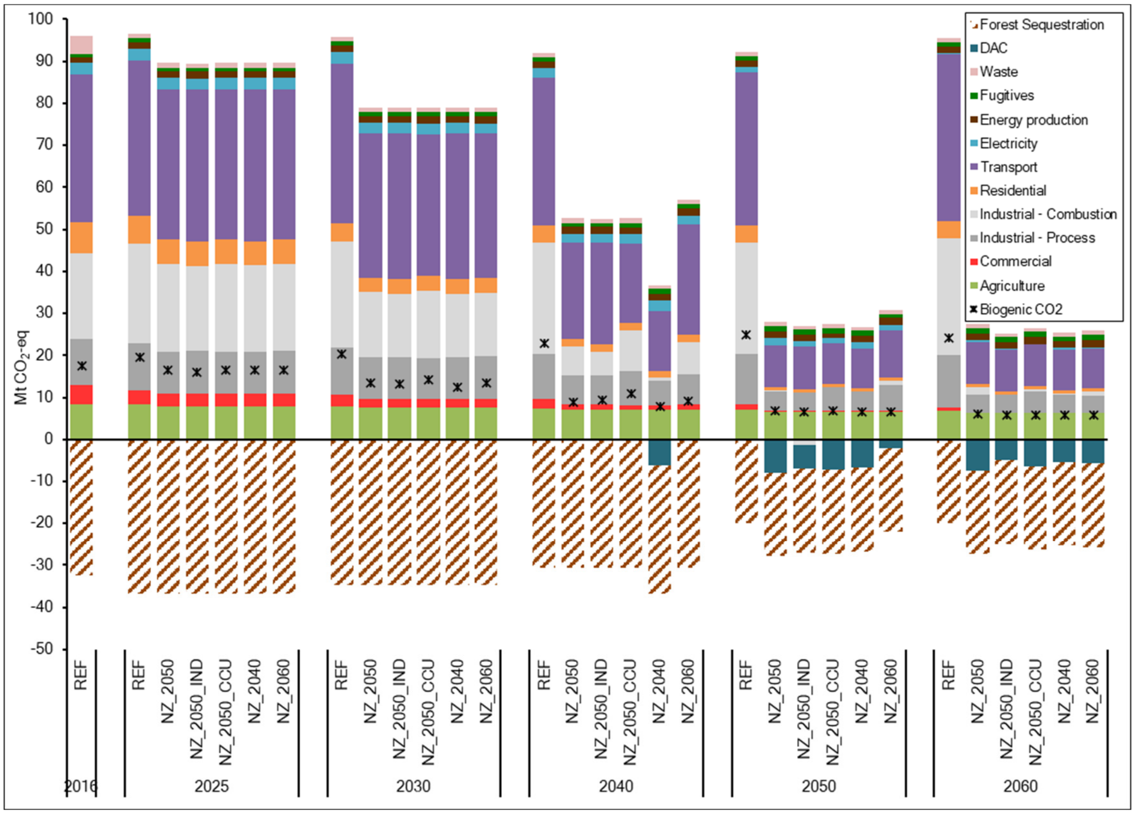


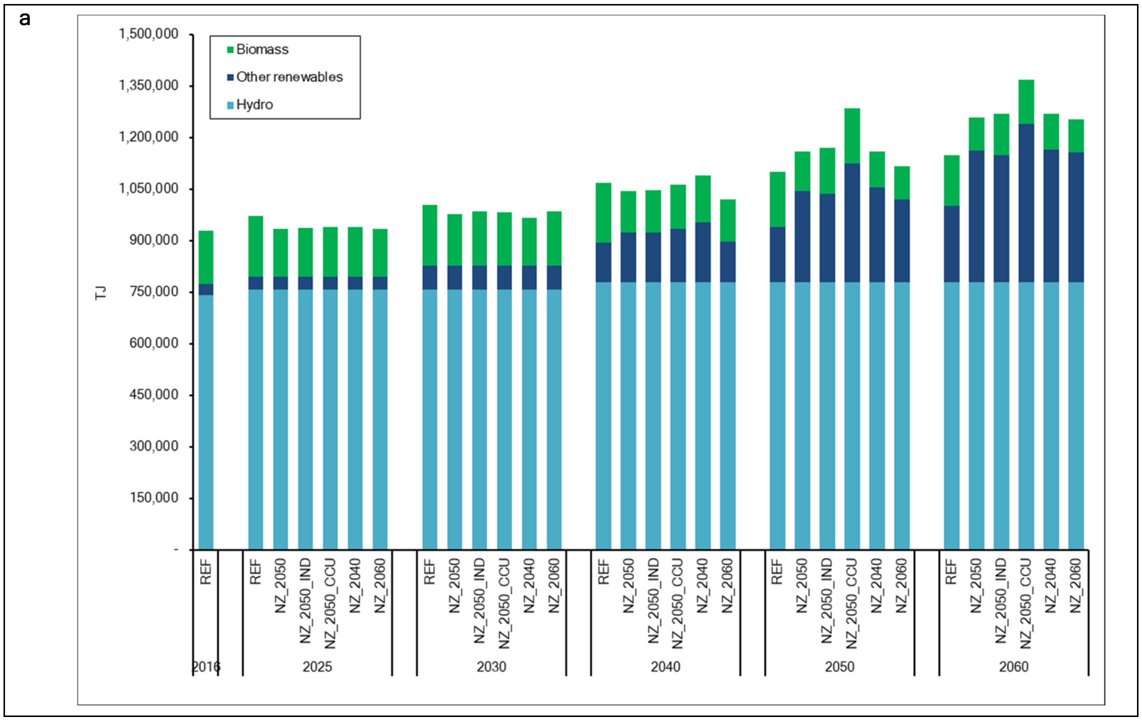
Figure 4.2 GHG emissions by sector for all scenarios

4.3.2 Primary energy production and final energy consumption

Primary energy production in Quebec from hydroelectricity, biomass, and other renewables (wind, solar) is depicted in Figure 4.3(a). The province also imports other forms of primary energy, such as crude oil and natural gas. In net-zero scenarios, total primary production (without imports) increases over time compared to the reference case, due to surging mitigation costs resulting from underlying constraints. In net-zero scenarios, the share of wind and solar is projected to increase significantly from 4% in 2025 to more than 30%, while the biomass share is expected to decline from 15% in 2025 to less than 10% by 2060, depending on the defined constraints. Fuel imports (not shown) decrease significantly in all NZ scenarios, as more renewables become available to meet the net zero target.

When compared to the REF scenario, final energy consumption decreases faster in scenarios with a stringent constraint (e.g., NZ_2040) than in scenarios with a less stringent target (e.g., NZ_2060) (Figure 4.3(b)). The reduction in final energy consumption is due to the adoption of alternative and more efficient technologies that utilize electricity or hydrogen as energy sources. In NZ_2050, the consumption of electricity, hydrogen, and non-energy products increases compared to REF in 2050, while the consumption of high GHG intensity energy sources decreases considerably. Synthetic fuels are relied upon in NZ_2050_CCU only, accounting for 3% of total energy consumption in 2050 and 2% in 2060, indicating it is the least cost available option to reuse captured industrial CO_2 when sequestration is unavailable. NZ_2050_CCU has the highest energy consumption in net-zero scenarios, with higher consumption of synthetic fuels, electricity, and hydrogen compared to other scenarios.

Total bioenergy consumption in the net-zero scenarios (Figure A-III 1) is lower than in the REF scenarios, due to the decrease in forest sequestration over time, so that biogenic emissions from the combustion of forest-based biomass and bioenergy cannot be offset by available forest sequestration, or the model prioritizes the use of available forest sequestration to temporarily absorb non-biogenic emissions (mainly in difficult to decarbonize sectors). Among net-zero scenarios in 2040, scenario NZ_2040 has the highest total bioenergy consumption (247 PJ) with a higher usage of solid biomass, and wood pellets. The NZ_2050_CCU scenario has the highest bioenergy consumption in 2050 compared to the other net-zero scenarios. This is attributed to the higher consumption of solid biomass and biomethane, which would be used to produce biobased electricity, heat and hydrogen. Except for NZ_2060, which undergoes a 13% increase, the total bioenergy consumption of net-zero scenarios decreases in 2060 compared to 2050. Overall, biomass and bioenergy contribute to achieving the GHG reduction target, particularly in target years with net-zero emissions (e.g., 2040 in NZ_2040) by primarily providing negative emissions using non-forest-based biomass in BECCS and, as a result, lowering GHG abatement costs.



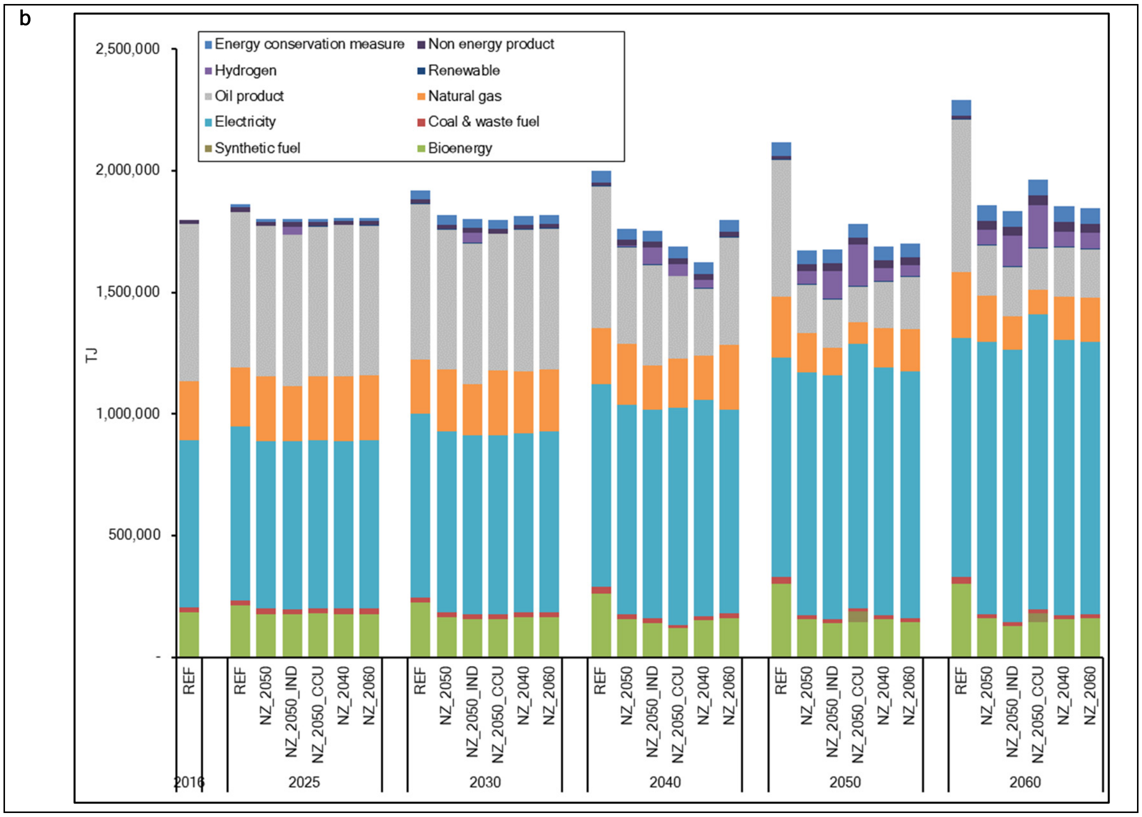


Figure 4.3 (a) Primary energy production in Quebec and (b) final energy consumption (HHV) in Quebec

In the net-zero scenarios, total electricity production increases substantially (by up to 20% in NZ_2050_CCU) in 2050 compared to the REF scenario (Figure A-III 2). The share of wind and solar is behind the increase in net-zero scenarios (up to 148% in NZ_2050_CCU) compared to the reference scenario. In 2050, by increasing the penetration of hydrogen (all net-zero scenarios), electricity (NZ_2040 and NZ_2060) and synthetic fuels (NZ_2050_CCU) in the industrial sector of the net-zero scenarios compared to REF scenario, other energy sources are reduced (Figure A-III 3). Industrial electricity consumption increases over time, representing between 4% and 7% in the net-zero scenarios compared to the REF scenario. Similarly, hydrogen consumption increases in the net-zero scenarios in 2060, reaching 174 PJ in the NZ_2050_CCU.

4.3.3 Hydrogen profile in the energy system

Figure 4.4 shows hydrogen production and consumption for all scenarios. Even though the REF scenario shows about 30 PJ of hydrogen production using primarily natural gas without CCS before 2040 (Figure 4.4(a)), most of the hydrogen produced is exported and not consumed within the energy system (Figure 4.4(b)). Natural gas-based hydrogen production in the REF scenario reduces over time and, by the end of the time horizon, is limited to biomethane and agricultural residues-based hydrogen. The model uses most of the hydrogen produced in the net-zero scenarios for export before 2040, except for NZ_2050_IND because of a minimum industrial hydrogen penetration constraint. In 2040, the hydrogen demand increases in net-zero scenarios (except NZ_2060) for industrial and transport sectors and is primarily met by natural gas with CCS-based hydrogen (blue hydrogen). A stringent GHG reduction constraint in the NZ_2040 scenario leads to the use of municipal waste with CCS-based hydrogen, which produces negative emissions and thus helps to rapidly decarbonize the system in 2040. On the other hand, in 2040, hydrogen production in NZ_2060 is around 6% of that in NZ_2050 because of postponing net-zero target. Hydrogen production in NZ_2060 decreases in 2040 compared to previous periods as GHG mitigation costs increase (Figure 4.7) and non-green based hydrogen becomes unfavorable.

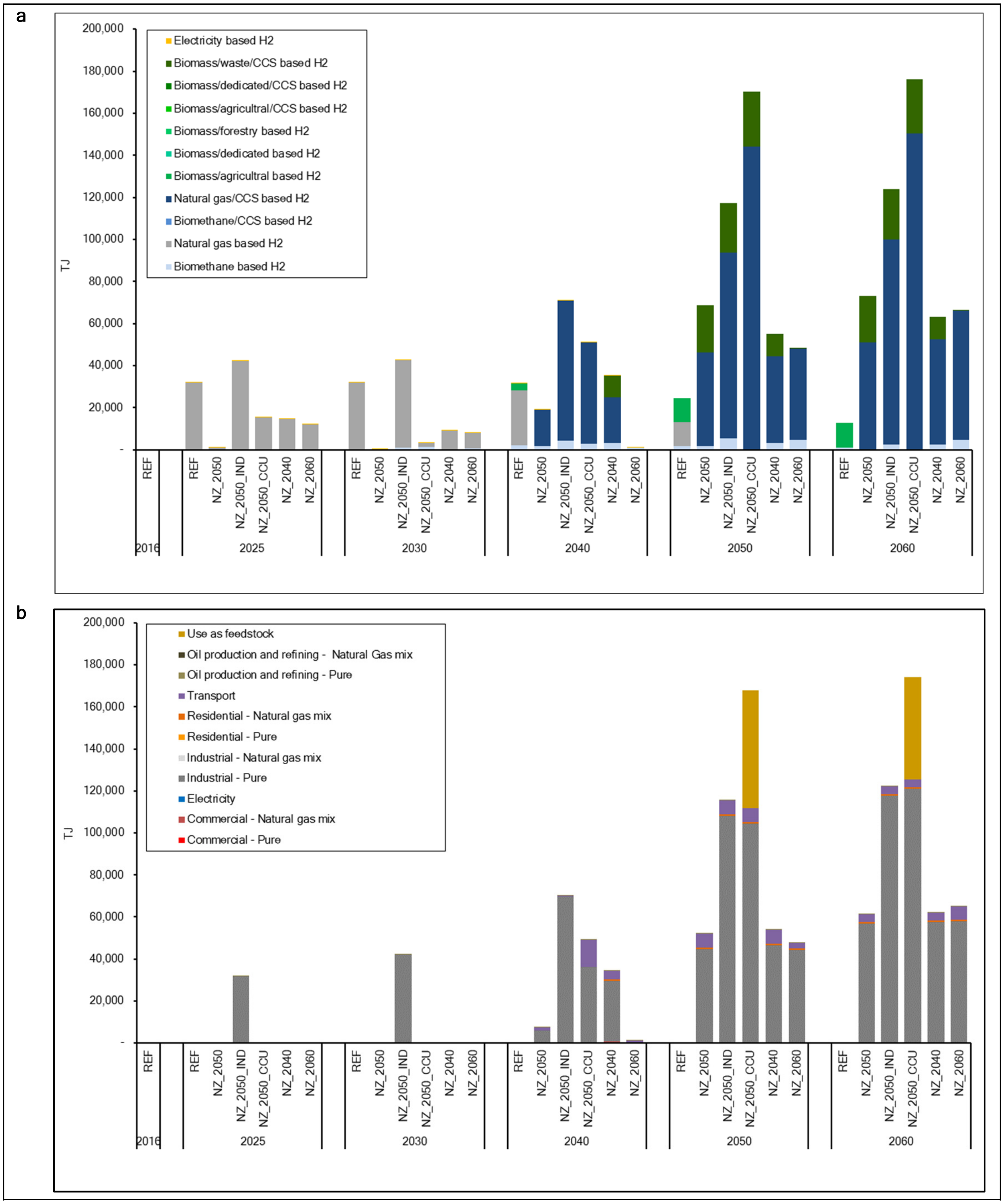


Figure 4.4 (a) Hydrogen production, and (b) hydrogen consumption for all scenarios

Regardless of chosen policy constraints, the amount of hydrogen produced and consumed in net-zero scenarios increases significantly in 2050 and 2060 when compared to previous periods, reaching more than 174 PJ in 2060 for NZ_2050_CCU. This shows the potential importance of hydrogen in decarbonizing the energy system. The hydrogen produced is mainly used for the industrial sector. In NZ_2050, the transport sector consumes 13% and 6% of the produced hydrogen in 2050 and 2060, respectively. NZ_2040 scenario uses 12% and 6% of produced hydrogen for the transport sector in 2050 and 2060, respectively. However, the share of hydrogen consumption in the transport sector increases from 5% in 2050 to 10% in 2060 for NZ_2060. More than 30% of produced hydrogen in 2050 of NZ_2050_CCU is used as feedstock for the consecutive synthesis processes. The model must decide whether to use or sequester the captured CO_2 from the industrial process (Figure A-III 5). However, since aquifer sequestration for onsite captured industrial emissions of NZ_2050_CCU has been disabled, CCU technologies could use the captured CO_2, which primarily use hydrogen as feedstock to produce synthetic fuels (c.f. DAC and allocation of negative emissions obtained from forest sequestration are other options for capturing and eventually sequestering industrial emissions, available in Figure A-III 5). Accordingly, the model can endogenously allocate available hydrogen to different sectors. In NZ_2050_CCU in 2050 and 2060, respectively, 62% and 69% of the hydrogen is still consumed in the industrial sector, indicating the need for hydrogen in the industrial sector's decarbonization in the absence of aquifer sequestration.

The penetration of industrial hydrogen of steam demand under different policy scenarios is shown in Figure 4.5. For NZ_2050, it is 27% in 2050, meaning that 27% of the total industrial steam would be supplied by hydrogen. NZ_2050_IND is required to have at least 70% penetration in 2050, whereas NZ_2050_CCU has 71% penetration in 2050, rising to 74% in 2060. The penetration ratio is 28% in 2050 and about 32% in 2060 for NZ_2040 and NZ_2060 scenarios respectively.

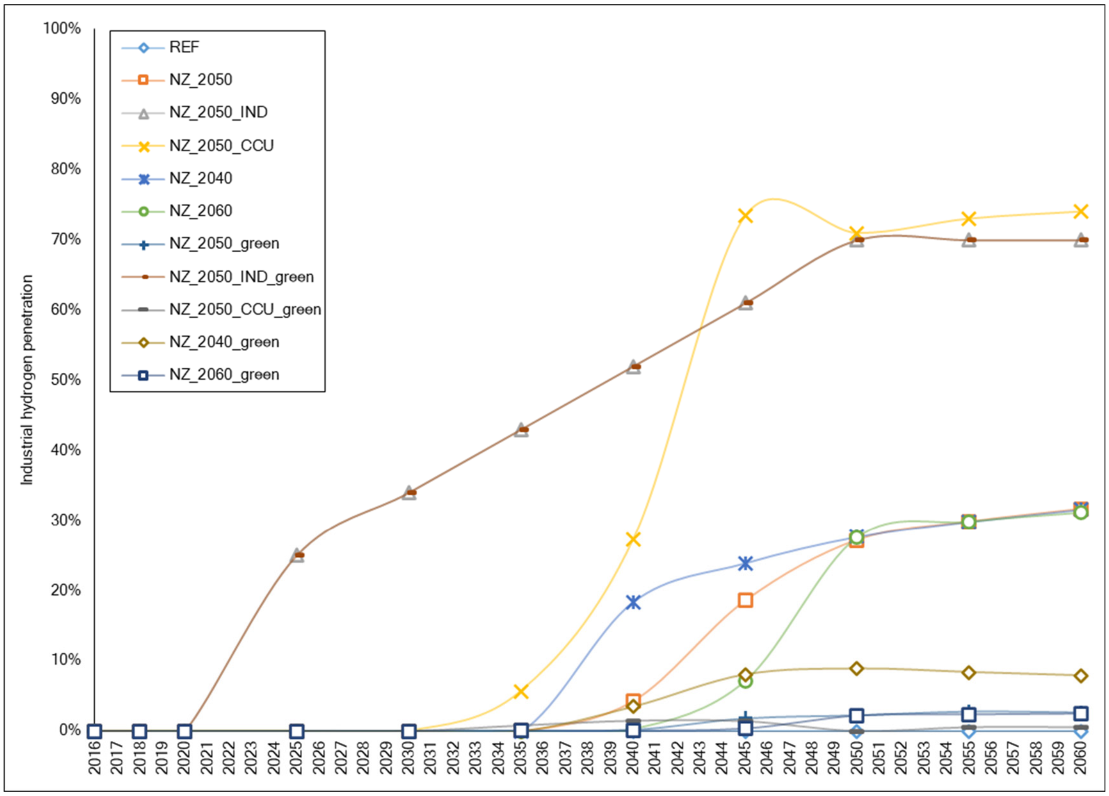


Figure 4.5 Industrial hydrogen penetration (% of steam) under different policy scenarios

4.3.4 Hydrogen technology mix

Figure 4.6 shows the merit order of hydrogen production technologies for each scenario and time period based on unit variable costs. These technologies were selected endogenously by NATEM from a pool of different available hydrogen technologies and defined constraints. The term "existing" refers to an already producing technology. In all scenarios except NZ_2040, existing electrolysis (ELC/PEM/RAG/DCN) technologies have the lowest unit variable cost ($3.5/GJ), making it the first hydrogen technology to be utilized (3 TJ to 46 TJ of hydrogen production). The biomass gasification (BIO/GASIF/CEN/STD) technology ranks second in the REF scenario in 2040, followed by standard SMR (NGA/BIOMTN/SMR/CEN/STD) and existing decentralized resources (NGA/DCN). A negative unit variable cost indicates that gains are higher than costs with BECCS, which is achieved by producing negative emissions (which could even be seen as the main product, while hydrogen is the by-product).

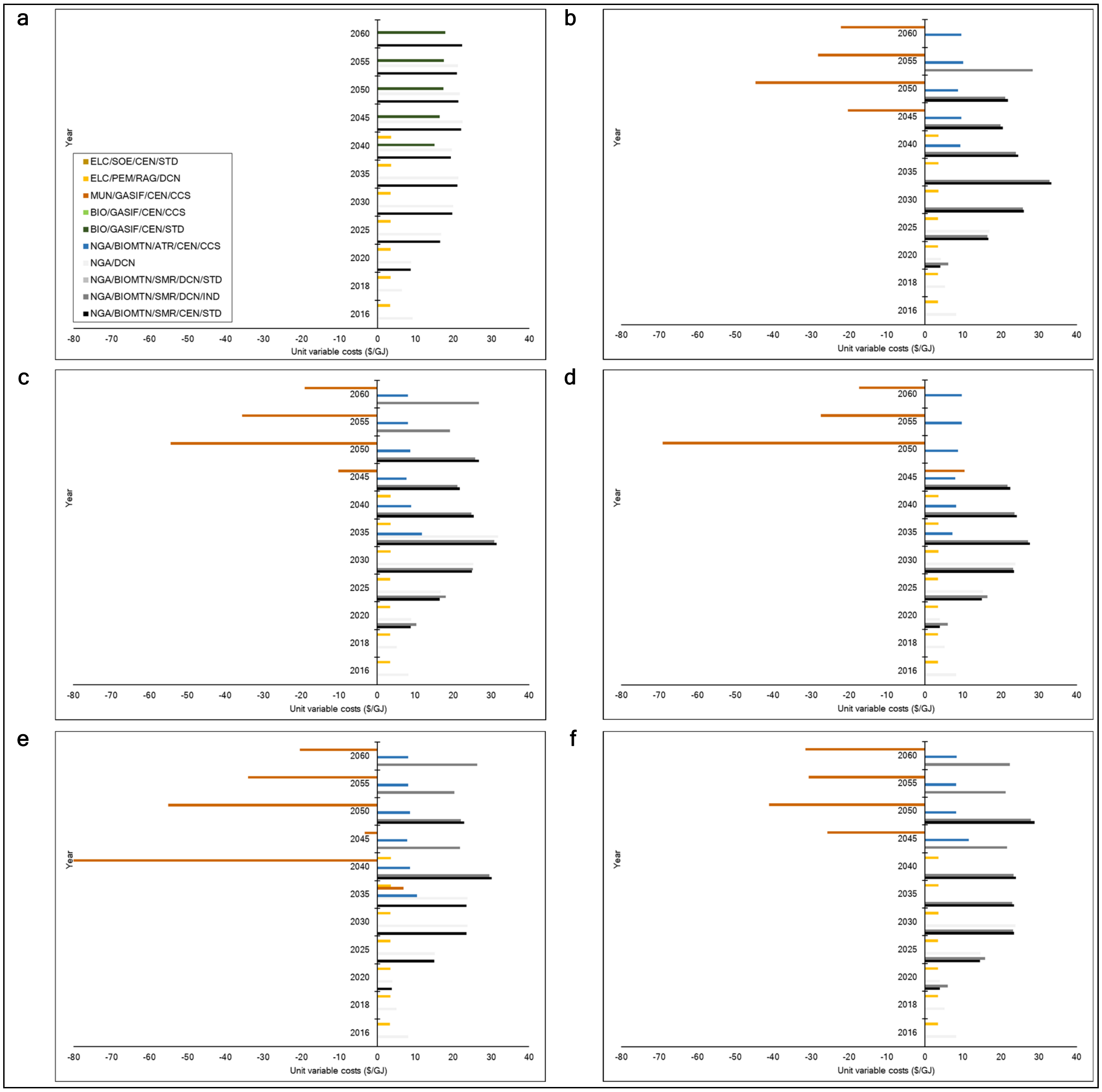


Figure 4.6 Merit order of hydrogen technologies, (a) REF, (b) NZ_2050, (c) NZ_2050_IND, (d) NZ_2050_CCU, (e) NZ_2040, and (f) NZ_2060

In 2040, municipal waste gasification (MUN/GASIF/CEN/CCS) represents the lowest unit variable cost (-$80/GJ) in NZ_2040, followed by biomethane ATR with CCS (NGA/BIOMTN/ATR/CEN/CCS), and biomethane SMR (NGA/BIOMTN/SMR/DCN/IND and NGA/BIOMTN/SMR/CEN/STD). This is because the model needs negative emissions from hydrogen production with BECCS to satisfy the stringent GHG reduction target (high GHG abatement cost, see Figure 4.7) envisioned in NZ_2040. After BECCS and existing technologies, blue hydrogen (NGA/BIOMTN/ATR/CEN/CCS) is the most widely used hydrogen producer technology. In scenarios with a high hydrogen production requirement, large-scale electrolysis (ELC/SOE/CEN/STD) only activates after implementing a green (no-fossil-fuels) policy (Figure A-III 8, NZ_2050_IND_green and NZ_2050_CCU_green), as it comes after (unlimited) natural gas in the merit order.

4.3.5 GHG abatement costs

Setting a strict 2040 GHG reduction target for NZ_2040 leads to a significant increase in marginal GHG reduction costs in 2040 (\$1150 per tCO_2-eq), while reducing abatement costs in 2050 (\$760 per tCO_2-eq) compared to NZ_2050 (Figure 4.7). Postponing the net-zero emissions target to 2060 (NZ_2060) results in lower mitigation costs before 2055 and higher costs after 2055 compared to NZ_2050 and NZ_2060. The application of a minimum 70% hydrogen penetration in the industrial sector steam for the NZ_2050_IND scenario and a CCU expansion constraint for the NZ_2050_CCU scenario results in higher mitigation costs in 2050 than the NZ_2050 scenario, as might be expected.

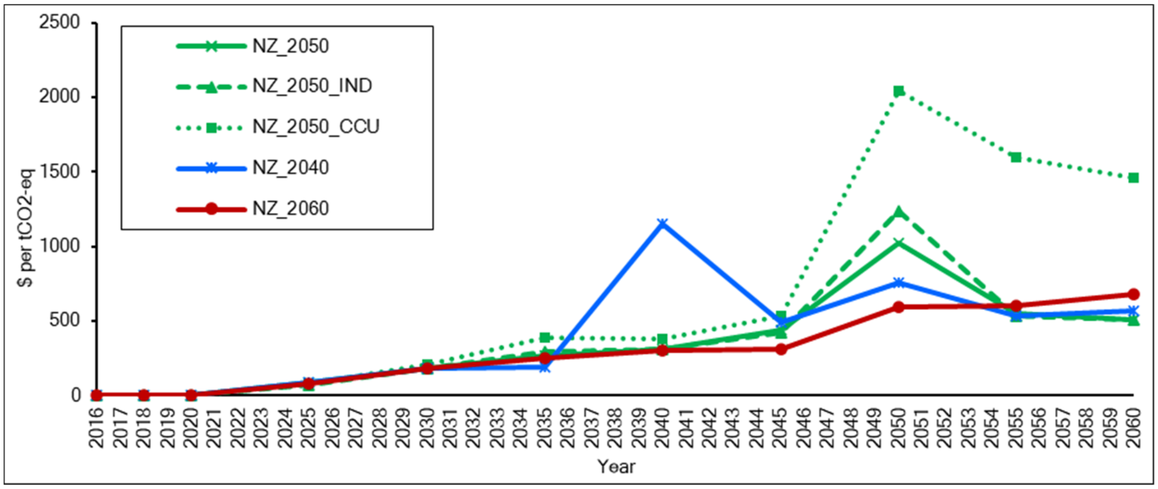


Figure 4.7 GHG mitigation costs (CAD per tCO_2-eq)

4.3.6 Green hydrogen policy

Hydrogen production decreases significantly when a green hydrogen policy is included for all scenarios except NZ_2050_IND_green (Figure A-III 7(a)), for which a minimum of 70% hydrogen is required for the industrial sector. Electrolysis using solid oxide electrolyzer cell (ELC/SOE/CEN/STD) is activated in NZ_2050_IND_green after 2025 or in NZ_2050_CCU_green after 2050 (Figure A-III 8) when the cost of GHG abatement reaches its maximum and a carbon-free energy carrier such as hydrogen could help to achieve the net zero emission target. After 2025, SMR technologies continue to produce hydrogen as they can use syngas or biomethane as a feedstock. The share of hydrogen usage (Figure A-III 7(b)) in the transport sector decreases in net-zero scenarios with a green hydrogen policy compared to the same scenario without green hydrogen constraints because the model must meet a minimum industrial hydrogen penetration of 70% after 2050 in NZ_2050_IND green and provide required hydrogen as feedstock for converting available industrial CO_2 to synthetic fuels or slag block in NZ_2050_CCU_green. (The by-product of the steel making process, known as steel slag, contains high levels of calcium and silica, which make it a viable substitute binder to produce construction blocks. The total CO_2 emitted per block is reportedly -0.23 kg for the slag-bonded concrete block, while it is 1.56 kg for the cement block (Mahoutian and Shao, 2016)).

A green hydrogen policy reduces reliance on DAC, when compared to the same scenario without the green hydrogen constraint, with the exception of the NZ_2050_CCU scenario (Figure A-III 9). For example, in 2050, the NZ_2050_green scenario requires 6% less CO_2 removal with DAC than the NZ_2050 scenario. In 2060, the reliance on DAC in the green hydrogen scenarios decreases by up to 8% in the NZ_2050 green scenario compared with to the NZ_2050_green scenario. The reliance on DAC in the NZ_2050_CCU_green scenario, on the other hand, increases over time relative to the NZ_2050_CCU scenario because the model requires the sequestration of additional industrial CO_2 emissions that cannot be economically converted to synthetic fuels or slag blocks. The green hydrogen policy also reduces the penetration rate of industrial hydrogen, except where constrained (Figure 4.5, NZ_2050_IND_green).

4.3.7 Carbon capture and usage

Carbon capture and usage (CCU) technologies and available carbon sequestration in NATEM-Quebec are shown in Figure A-III 5. The blocking of deep saline aquifers for industrial CO_2 emissions in NZ_2050_CCU and NZ_2050_CCU_green could either direct industrial emissions towards sequestration by forestry or offer the possibility of utilizing captured CO_2 (from industry or from DAC) through available CCU technologies. Although this substantially increases GHG abatement costs (Figure 4.7), CCU technologies use around 3.2 $MtCO_2$ to produce mainly synthetic jet fuel based on the Fischer-Tropsch conversion process (Figure 4.3(b) and Figure A-III 10) compared to 12.5 $MtCO_2$ going to industrial CCS in NZ_2050.

4.4 Discussion

The penetration of industrial hydrogen is about 27% of steam demand to reach net-zero emission by 2050 (NZ_2050). Forcing a 70% penetration of industrial hydrogen (NZ_2050_IND) while facilitating the decarbonization of the industrial sector, reduces the need for carbon removal through DAC in 2050. This results in additional GHG abatement costs of 220 CAD/tCO_2-eq in 2050, but GHG abatement costs drop to the NZ_2050 scenario level after 2050. Incentivizing CCU (NZ_2050_CCU) leads to an industrial hydrogen penetration of 71% and synthetic fuels production in 2050. This would not result in industrial GHG reduction, but it slightly reduces transportation emissions and the need for DAC compared to NZ_2050. CCU expansion increases GHG abatement costs by 560 CAD/tCO_2-eq in 2050 and impedes cutting down GHG abatement costs after 2050. Hydrogen is mostly consumed in the industrial sector in NZ_2050_CCU, indicating the importance of hydrogen in the industrial sector's decarbonization if CO_2 storage in deep saline aquifers is not allowed. Accelerating the net-zero emission target (NZ_2040) requires a higher penetration of industrial hydrogen between 2040 and 2050 compared to NZ_2050. Net-zero by 2040 also results in 50% and 13% reductions in industrial GHG emissions in 2040 and 2050, respectively, compared to NZ_2050. GHG abatement costs of NZ_2040 increase in 2040 and then decrease in comparison to NZ_2050. Postponing the net-zero target (NZ_2060) reduces industrial hydrogen penetration before 2050, after which it reaches the same level as NZ_2050 in 2050. This also postpones the need for GHG reduction and DAC in 2050. GHG abatement costs gradually increase in NZ_2060, reaching a peak of 680 CAD/tCO_2-eq in 2060. A policy only allowing green hydrogen drastically reduces hydrogen penetration, unless hydrogen use is also mandated. In net-zero green scenarios, industrial GHG emissions and the need for DAC decrease slightly, and GHG abatement costs increase as expected. NZ_2050_CCU_green, however, follows the same amount of industrial GHG emissions and the need for DAC as NZ_2050_CCU in 2050.

In this study, the model allowed unlimited use of CCS technologies in the industrial sector, which may be unrealistic in the short term. Consequently, this analysis shows comparatively reduced GHG mitigation costs than our earlier research, which was more restrictive in its CCS options (Kouchaki-Penchah, Bahn, Vaillancourt, *et al.*, 2023).

There is an important trade-off between trying to minimize fossil fuels usage and DAC on one side, and on the other side, trying to minimize abatement costs. High reliance on hydrogen technologies is expensive because it allocates investment to low-density technologies (wind and solar) that require more resources (metals etc.) and undoubtedly have environmental impacts of their own. Thus, Net Zero policies based on high reliance on hydrogen technologies carry some risk of being counterproductive, relative to policies that allow more reliance on CCS and DAC, although the latter also have risks linked to CO_2 transportation and storage.

Another significant aspect to consider is the trade-off between forest residue as a potential carbon sink on its own, and forest residue as a source of negative-emissions hydrogen. On the one hand, in-forest sequestration offers cost-effective carbon storage but may pose a fire hazard (or otherwise decompose) after 2050. On the other hand, BECCS provides a low-cost source of hydrogen relative to electrolysis, with potentially longer-duration carbon storage as CO_2, but it also carries certain risks. Thus, determining which option is superior remains unclear, even from a strictly environmental standpoint.

The current setup of NATEM-Quebec defines CAPEX in immaterial terms without providing feedback to the industries within the model (cement, steel, mining) that would be heavily solicited for the expansion of new energy infrastructure in all scenarios. We acknowledge this limitation in our study, which could be addressed in future studies. As discussed in our previous study (Kouchaki-Penchah, Bahn, Vaillancourt, *et al.*, 2023), import prices in the version of the NATEM model that was used do not rigorously reflect the corresponding GHG mitigation costs, potentially leading to burden shifting, as the model does not account for process emissions from imported fuels.

Besides the techno-economic considerations of hydrogen as a decarbonization strategy, there are other social and ecological factors to consider (Simoens, Fuenfschilling et Leipold, 2022 ; Correa Hackenhaar *et al.*, 2022). As net zero strategies grapple with technological advances (such as hydrogen fuel, CCU, CCS, etc.) and their deployment through vast and complex global supply chains, the social and ecological questions must also be addressed to avoid unintended weak sustainability outcomes for future generations (Seto *et al.*, 2016 ; Unruh, 2002). Incorporating the socio-ecological elements into techno-economic analyses is a necessary next step (Babí Almenar *et al.*, 2023). Doing so will address the gap between resolving mid-point impacts in the energy sector and end-point damage at the societal level. Future work on the role of hydrogen must consider the way in which decarbonization strategies applied to industrial silos may have unintended environmental consequences, which may not necessarily create a more sustainable future. Achieving this calls for an integrated modeling approach, convening a suite of affected sectors and impact categories such as land use change, water and resource depletion (Elliot *et al.*, 2022). Moreover, understanding how these strategies are woven into long-term, robust, strong sustainability policies requires inter-, trans-, and cross-disciplinary engagement with actors beyond the techno-economic sphere.

4.5 Conclusion

This study shows how alternative policies could affect the energy transition toward a net-zero economy, focusing on the role of hydrogen, using a version of the NATEM model for Quebec that includes biogenic carbon accounting. Increasing the penetration of hydrogen as a source of industrial steam results in reducing GHG emissions from the industrial sector, whereas a CCU expansion policy keeps industrial emissions relatively high so that available industrial CO_2 could be converted to synthetic fuels and used in subsequent transportation and industrial processes. CCU expansion policy also leads to the highest energy consumption in net-zero scenarios, with higher consumption of synthetic fuels, electricity, and hydrogen compared to other scenarios. The share of other renewables such as wind and solar of total primary energy production increases over time horizon in net-zero scenarios, showing the need to invest in additional renewable electricity in Quebec. Biomass and bioenergy also play an essential role in achieving net-zero targets through providing negative emissions using non-forest-based biomass in BECCS, while forest-based biomass provides in-forest sequestration preferentially (the decomposition emissions are sufficiently delayed beyond the modeling time horizon in the biogenic carbon accounting framework). Although the demand for blue hydrogen increases over time in net-zero scenarios, an ambitious GHG reduction target leads to an increase in the use of BECCS (green hydrogen using waste), which can produce negative emissions and rapidly decarbonize the system.

The use of hydrogen in the industrial sector, known as difficult to decarbonize, reduces industrial emissions and reliance on direct air capture. Clustering industrial plants to use captured CO_2 as a feedstock for synthetic fuel production may not reduce industrial GHG emissions, but it does provide an opportunity to use captured CO_2 instead of sequestering it in deep saline aquifers. However, it may further postpone industrial decarbonization. Even though increasing the penetration of industrial green hydrogen increases GHG abatement costs compared to NZ_2050, it minimizes industrial GHG emissions and the need for DAC among all net-zero scenarios by 2050. Thus, hydrogen provides a key trade-off between reliance on direct air capture, reliance on carbon storage, reliance on wind and solar buildout, the inter-sector allocation of residual emissions, and the overall cost of achieving emission targets. Net-zero emissions can be achieved by increasing energy efficiency through technological alternatives, decarbonizing electricity generation, imposing electrification, deploying negative emission technologies, and increasing hydrogen penetration. Hydrogen plays an important role in achieving ambitious net-zero emission targets by reducing industrial GHG emissions, minimizing reliance on DAC, and enabling alternative pathways for decarbonization, especially in situations where electrification is not feasible or expensive electricity storage becomes necessary. Further research should address questions related to sensitivity analysis, such as the optimal allocation of bioenergy and the hydrogen merit order, which highly depend on input parameters for hydrogen technologies, as well as competing end-uses like direct electrification in industry and alternative bioenergy pathways.

CHAPTER 5

A BROADER DISCUSSION

The transition towards decarbonization has become a global imperative, and the role of the forest sector in this process has gained significant attention. In Quebec, the forest sector holds significant importance, and as a substantial portion of forests being publicly owned, the government plays an important role in formulating strategies to effectively manage these forests for climate change mitigation purposes. This thesis proposes an innovative integrated framework to analyze the potential contribution of the forest sector in facilitating decarbonization pathways, focusing on the case of Quebec. By addressing three key research questions, namely the contribution of forest-based bioenergy, the impact of assuming biogenic carbon neutrality, and the role of biomass-based hydrogen, this study seeks to shed light on the complex dynamics and opportunities within the forest sector.

Following a carbon neutrality assumption, forest-based bioenergy has emerged as a promising avenue for achieving deep decarbonization in Quebec. Previous studies have emphasized the potential of second-generation biofuels derived from lignocellulosic feedstock, which offer improved availability, affordability, and sustainability compared to first-generation biofuels. This study integrates a range of different primary and secondary forest-based bioenergy conversion technologies in NATEM-Quebec. The findings indicate that conversion processes such as gasification and Fischer-Tropsch catalytic conversion exhibit cost-competitive production of bioethanol and liquid transportation fuels. Moreover, forest-based bioenergy aligns with the principles of a circular economy, allowing for the utilization of low-quality roundwood and surplus forest growth as feedstock. This not only enhances the efficiency of the forest value chain but also addresses the declining demand for traditional forest products, providing further incentives for the adoption of forest-based bioenergy. However, it is crucial to consider potential limitations and trade-offs associated with forest-based bioenergy. A comprehensive evaluation is necessary to accurately assess the competition for biomass resources between industrial usage and bioenergy production, particularly concerning forest industry residues. To address this, it is essential to incorporate non-energetic wood products and competing materials into the model along with their trading profiles, effectively accounting for this competition. By considering a broader range of factors, such as the utilization of biomass for non-energy purposes and alternative materials, a more comprehensive understanding of the dynamics and trade-offs involved in biomass allocation can be achieved. Indirect land-use change and the impact on carbon sequestration profiles should be taken into account when increasing feedstock availability. While the emphasis in recent studies, including the second chapter of this thesis, has predominantly been on GHG emissions, it is crucial to acknowledge that environmental impact categories encompass a wider range of burdens that can have both positive and negative effects. Bioenergy systems, as outlined by Creutzig et al. (2015), directly impact local and global climates through various factors. These include the emission of GHGs from fossil fuels used in biomass production and conversion, as well as from biomass combustion. Land disturbances contribute to CO_2 exchanges between the atmosphere and ecosystems. Non-CO_2 GHGs, such as black carbon and chemically active gases, result from biomass combustion and land management practices. Moreover, modifications to the land surface, affecting properties like albedo and surface roughness, lead to climate forcing. Adopting a life cycle approach is crucial to comprehensively assess the GHG emissions and uptake associated with bioenergy and BECCS technologies and accurately determine their overall contribution to mitigating climate change (NASEM, 2019).

Chapter 3 assessed the implications of the assumption of biogenic carbon neutrality on decarbonization pathways. The assumption of biogenic carbon neutrality has been a subject of debate and raises questions regarding its impact on decarbonization pathways. While bioenergy systems have often been treated as carbon neutral, it is essential to recognize that the carbon balance is contingent upon various factors, including the characteristics of the bioenergy system, soil and climate conditions, vegetation cover, and land-use history. The accuracy of assumptions regarding biogenic carbon neutrality is crucial for making informed decisions and avoiding biased conclusions. By not assuming carbon neutrality, the short-term emissions associated with bioenergy production may appear higher, especially in regions with lower forest coverage or sequestration potential. Importing bioenergies without sufficient carbon sink capacity can further increase biogenic emissions, potentially exacerbating the situation. To ensure unbiased decision-making, it is necessary to incorporate all biogenic carbon flows (emissions and uptakes) into global and national roadmaps towards net-zero CO_2 emissions. This requires a comprehensive assessment of the carbon sequestration potential of forests, the lifespan of harvested wood products, and the overall carbon balance associated with forest management practices. The present study enabled the inclusion of LULUCF, specifically addressing forest carbon stocks and changes in biomass and dead organic matter pools over time based on selected forest management strategies, as well as accounting for natural disturbances like wildfires and SBW infestations by integrating CBM-CFS3 and NATEM-Quebec models. However, it is important to note that this study did not encompass croplands, grasslands, wetlands, and settlements. Including other LULUCF strategies as potential CDR methods could be incorporated into the energy system model. The developed approach takes into account forest net emissions, GHG emissions from harvesting, transportation, and manufacturing, as well as emissions from residue decomposition and biomass combustion. Nevertheless, this study did not consider other environmental impacts such as short-lived climate forcers (e.g., black carbon and nitrogen monoxide), or the climate-forcing effects resulting from changes in the land surface's biophysical properties (e.g., alterations in albedo). In this study, the decomposition emissions of HWPs were not taken into account. To accurately consider these emissions, HWP carbon models would need to be employed. Nonetheless, the study envisions a circular economy for HWPs usage in the future, whereby HWPs are transformed into another product (resulting in no biogenic emissions) or utilized for energy purposes (resulting in biogenic emissions) at the end of their lifespan, rather than being disposed of in landfills. The integrated approach developed in this study does not consider the potential substitution effect resulting from the use of HWPs instead of non-wood materials such as cement and steel. Future research could enhance the model by incorporating HWPs and substituted materials, thereby capturing the broader impacts and benefits of utilizing HWPs within the context of CDR.

CDR strategies through measures in agriculture, forestry and other land use could be sustained for decades, but not for very long because these sinks will eventually saturate (Riahi *et al.*, 2022 ; Lecocq *et al.*, 2022). Recent years have witnessed a significant increase in forest disturbances (NRCan, 2022), casting doubt on the accuracy of using data from previous decades to calculate future disturbance rates in Canadian forests. Future research should examine the rising levels of disturbances, particularly considering the impact of a changing climate on forest disturbance patterns (Seidl *et al.*, 2017). The current setup of NATEM-Quebec allows leaving additional residues in the forest without considering the potential for increased fire risk. This limitation of the developed integrated approach could be addressed by incorporating feedback from NATEM-Quebec into the CBM-CFS3 model. In addition to the mentioned limitations, there are significant uncertainties surrounding indirect emissions, potential impacts on food security (first-generation biofuels), effects on biodiversity and land conservation, competition for water resources, and social equity and acceptance concerns (Sanchez et Kammen, 2016). These aspects should be carefully examined in future studies to gain a comprehensive understanding of the broader implications associated with bioenergy technologies. Integrated assessment models (IAMs) could also help to identify efficient pathways for future work, as they model cost-effective strategies for achieving specific climate targets while taking into account intersectoral competition for biomass and land carbon balances related to land use and biomass provision.

Biomass-derived hydrogen shows great potential as a substantial element in Quebec's shift towards sustainable energy. The penetration of industrial hydrogen is projected to play a substantial role in achieving net-zero emissions by 2050. Biomass gasification with CCS, coupled with hydrogen production, can provide a renewable and negative emission alternative to fossil fuels. By using biomass feedstock, such as municipal waste, agricultural residues and dedicated energy crops, hydrogen can be produced and provide negative CO_2 emissions, contributing to the decarbonization of various sectors, including transportation and industry.
Policymakers can effectively advance the goal of net-zero emissions by leveraging the benefits of hydrogen, such as reducing industrial GHG emissions, reducing reliance on DAC, and

enabling alternative decarbonization pathways. However, the trade-off between minimizing fossil fuel usage and deploying DAC technology, on the one hand, and minimizing abatement costs, on the other hand, presents a challenge for Net Zero policies. Reliance on hydrogen technologies, which often require investments in low-density renewable sources like wind and solar, can be expensive and have their own environmental impacts. Hence net-zero policies based on high reliance on hydrogen technologies carry some risk of being counterproductive, relative to policies that allow more reliance on CCS and DAC, although the latter also have risks linked to CO_2 transportation and storage. Another important aspect to consider is the trade-off between using forest residue as a carbon sink or as a source of negative-emissions hydrogen. In-forest sequestration offers cost-effective carbon storage, but it may pose risks such as fire hazards or decomposition after 2050. On the other hand, BECCS can provide low-cost hydrogen and potentially longer-duration carbon storage, but it also carries certain risks. Determining the superior option remains unclear, even from an environmental perspective. Therefore, it is essential to carefully evaluate the benefits and drawbacks of different strategies, considering not only their techno-economic aspects but also their social, ecological, and safety implications.

In CHAPTER 4, the model allowed unlimited use of CCS technologies in the industrial sector, which may be unrealistic in the short term. Consequently, this analysis shows comparatively reduced GHG mitigation costs than the earlier study (section 3.3.5 in CHAPTER 3), which was more restrictive in its CCS options. Besides, as highlighted in the CHAPTER 3, import prices in NATEM do not adequately consider the costs associated with GHG mitigation. This limitation can potentially result in burden shifting, as the model does not take into account the process emissions stemming from imported fuels. Furthermore, the current setup of the model used in this study defines CAPEX in immaterial terms without providing feedback to the industries within the model. The expansion of new energy infrastructure could heavily solicit the material industries.

In the pursuit of net zero strategies, it is crucial to address the challenges posed by technological advancements and their implementation within global supply chains. While hydrogen, CCU, CCS, and other technologies hold promise, it is essential to consider the social and ecological aspects to avoid unintentional weak sustainability outcomes for future generations (Seto *et al.*, 2016 ; Unruh, 2002 ; Correa Hackenhaar *et al.*, 2022 ; Simoens, Fuenfschilling et Leipold, 2022). This necessitates incorporating socio-ecological elements into techno-economic analyses, bridging the gap between resolving impacts in the energy sector and understanding their societal-level consequences.

CONCLUSION

This thesis proposes an integrated framework to help decision makers analyze the contribution of the forest to deep decarbonization pathways. The integrated approach eliminates the carbon neutrality assumption in previous literature since assuming carbon neutrality for forest biomass can result in accounting errors and biased decision-making. Following the developed approach, this research conducts a comprehensive techno-economic study of different hydrogen pathways that consider the GHG emissions and uptakes associated with forest management, BECCS, and biogenic CO_2 flows.

The long-term role of forest-based bioenergy technologies was measured using a bottom-up energy model and following a carbon neutrality assumption. After a comprehensive overview of bioenergy conversion processes, a detailed inventory of techno-economic data was provided and implemented in the energy system model. This study identifies the transportation sector as the primary contributor to GHG emissions over the time horizon. Besides, decarbonizing heavy industry is the most challenging task in achieving GHG reduction targets in Quebec. Extensive electrification is required to reach the GHG reduction targets. The bioenergy share is expected to increase considerably in the transportation and industrial sectors, cutting down on the need to reduce GHG emissions. Forest-based bioenergies such as cellulosic bioethanol, biobased heat, FT diesel, and electricity as a co-product can effectively support this energy transition. The Quebec government could envision a greater penetration of bioenergy in its 2030 plan for a green economy. This study reveals that forest-based bioenergy should be an important component of the decarbonization strategy of Quebec. Other world regions with a declining trend for traditional forest products should also consider such a strategy.

The second objective of this dissertation involved integrating biogenic CO_2 flows into the energy system model to address the carbon neutrality assumption commonly found in previous literature. The output of the CBM-CFS3 model was used to model different forest management approaches for the province of Quebec in Canada that would lead to different biomass availability for bioenergy and forest net emissions, in order to see if and how this biomass would be used within the energy system over the time horizon. This study highlighted that taking forest sequestration into account can help alleviate the decarbonization effort by flattening GHG trajectories and allowing policymakers to use available forest sequestration for difficult-to-decarbonize sectors. Including biogenic CO_2 emissions in NDCs is recommended since excluding them affects the solution. It can also affect the solution by choosing alternative BECCS. It is necessary to identify the most promising forest management strategy before investing in BECCS because the model employs various methods of biomass utilization based on available biomass and the sequestration potential. When available forest sequestration cannot offset biogenic CO_2 emissions, GHG abatement costs increase exponentially. Including biogenic emissions reduces biomass and bioenergy usage in GHG scenarios. Therefore, assuming biogenic carbon neutrality may result in biased decision-making because it allows the model to use more biomass without being constrained by biogenic CO_2 emissions. Investing in BECCS, DAC, or other negative emission technologies faces multiple barriers in the short term, but shifting to forest management strategies that carry a lower cost than other NETs could potentially make it easier to limit warming to 2°C after 2030 and achieve net-zero emissions by 2050. The goal of net-zero emissions for Quebec by 2050 can be achieved by improving energy efficiency using technological alternatives, decarbonizing electricity generation, massive electrification, and deploying negative emission technologies such as forest management strategies with high forest sequestration. More stringent emission reduction targets could be adopted before 2030. It is also recommended that the Canadian forest sector be fully integrated into an energy system model to successfully plan the following steps for clean air and a strong economy. The proposed integrated approach can be adopted in any country using a TIMES approach in conjunction with a carbon budget model. Furthermore, the detailed approach employed for modeling forest-based bioenergy and BECCS can be easily extended to various regional contexts by updating associated costs.

The third objective of this dissertation involved demonstrating how alternative policies could affect the energy transition by focusing on the role of biomass-based hydrogen and following the developed integrated approach. Subject to the constraints chosen in this research, hydrogen is essential in achieving the target of net-zero emissions, regardless of the chosen strategy. The use of hydrogen in the industrial sector, a sector known to be difficult to decarbonize, alleviates the effort to reduce emissions and reduces reliance on direct air capture. Clustering industrial plants to use captured CO_2 as a feedstock for synthetic fuel production may not reduce industrial GHG emissions, but it offers the opportunity to use captured CO_2 instead of sequestering it in deep saline aquifers. However, it may further postpone the decarbonization of the industry, as the demand for CO_2 for synthetic fuel production requires the use of GHG-intensive energy sources. Net-zero emission scenarios were also analyzed in the absence of fossil fuel-based hydrogen. Even though increasing industrial green hydrogen penetration increases GHG abatement costs, it minimizes industrial GHG emissions and the need for DAC among all net-zero scenarios by 2050. Green hydrogen, in addition to blue hydrogen, can play a crucial role in achieving ambitious net-zero emission targets. Where electrification is not feasible, or energy storage is required, electrolysis could be adopted more widely.

The forest sector holds significant potential in facilitating decarbonization pathways, with forest-based bioenergy and sequestration potential playing a pivotal role. Forest-based bioenergy offers a renewable and sustainable alternative to fossil fuels while promoting the efficient utilization of forest resources. However, careful evaluation of feedstock availability, carbon sequestration dynamics, and competition for biomass is essential to ensure a balanced approach. The assumption of biogenic carbon neutrality should be critically assessed, taking into account regional characteristics and carbon balance considerations. Biomass-based hydrogen, although promising, requires careful consideration of cost and resource requirements, ensuring a comprehensive evaluation of alternative decarbonization strategies. By harnessing the potential of the forest sector, Quebec can take significant strides towards achieving its decarbonization goals, contributing to a sustainable and low-carbon future.

APPENDIX I

SUPPORTING INFORMATION
THE CONTRIBUTION OF FOREST-BASED BIOENERGY IN ACHIEVING DEEP DECARBONIZATION: INSIGHTS FOR QUEBEC (CANADA) USING A TIMES APPROACH

Part A

A comprehensive set of techno-economic data of primary and secondary forest-based bioenergy technologies is tabulated in Table A-I 1 and Table A-I 2, respectively.

Table A-I 1 Techno-economic data of primary forest-based bioenergy technologies

Technology	Conversion process	Forest industry residues	Hogfuel	Chips	Firewood	Slash	Pulp and paper waste	Spent liquor	Energy input	Bioenergy	EFF (Out/Input)	CEFF (Input fuel/Out)	Investment cost	Fixed operating cost	Variable operating cost	Cost unit	Life Time	Availability factor	Reference
Biomass HTL. Upgrading system 69.9 MGGEPY	Hydrothermal liquefaction	*	*	*	*	*			Electricity, Natural gas	Hydrocarbons	0.66	0.12	56.3	5.4	4.1	mCAD/PJ	20	0.91	(Zhu et al., 2014)
Co-Gasification. Methanol grade AA. Black liquor. Crude glycerol	Co-Gasification							*	Electricity	Biomethanol	0.79	1.27	133.6	1.6	5.9	mCAD/PJ	20	0.97	(Carvalho et al., 2018)
Fast pyrolysis and hydroprocessing 35 MGPY	Fast pyrolysis	*	*	*	*	*			Electricity, Natural gas	Gasoline(bio), Biodiesel	0.55	0.27	58.5	4.2	3.7	mCAD/PJ	30	0.91	(Li et al., 2017 ; Wright et Brown, 2019)
Fermentation. Butanol Production	Fermentation						*		Heat, Natural gas	Butanol(bio), Heat	0.92	1.22	326.9	19.0	9.4	mCAD/GW	30	0.96	(Levasseur et al., 2017)
Fermentation. Ethanol. Enzyme. Dilute-acid 53.4MGPY	Fermentation	*	*	*	*	*				Cellulosic bioethanol, Electricity	0.37		87.5	4.8	12.6	mCAD/PJ	20	0.91	(Li et al., 2018 ; Kazi et al., 2010)
Fermentation. Ethanol. Enzyme. NREL 61MGPY	Fermentation	*	*	*	*	*				Cellulosic bioethanol	0.43		86.1	4.9	5.6	mCAD/PJ	20	0.91	(Li et al., 2018 ; Humbird et al., 2011)
Fischer-Tropsch. Catalytic. Hydroprocessing. High temperature. Flow gasifier 41.7MGPY	Gasification/Fischer-Tropsch	*	*	*	*	*				FT diesel, Electricity	0.53		119.7	2.8	2.4	mCAD/PJ	20	0.91	(Swanson et al., 2010)
Fischer-Tropsch. Catalytic. Hydroprocessing. Low temperature. Fluidized bed gasifie 32.3MGPY	Gasification/Fischer-Tropsch	*	*	*	*	*				FT diesel, Electricity	0.43		122.2	2.9	3.2	mCAD/PJ	20	0.91	(Swanson et al., 2010)
Gasification facility. Gasifier + methanation. Wood	Gasification/methanation	*	*	*	*	*				Syngas, Electricity	0.55		3539.2	40.4	118.0	mCAD/GW	20	0.96	(Panos et Kannan, 2016)

Continued

Table A-I 1 Continued.

Technology	Conversion process	Forest industry residues	Hogfuel	Chips	Firewood	Slash	Pulp and paper waste	Spent liquor	Energy input	Bioenergy	EFF (Out/Input)	CEFF (Input fuel/Out)	Investment cost	Fixed operating cost	Variable operating cost	Cost unit	Life Time	Availability factor	Reference
Gasification facility. Gasifier + methanation. Wood. Electrolyser	Gasification/methanation	*	*	*	*	*			Electricity	Syngas	0.54	0.85	4317.9	57.4	167.5	mCAD/GW	20	0.96	(Panos et Kannan, 2016)
Gasification.Wood.20MW	Gasification	*	*	*	*	*				Syngas, Electricity, Heat	0.86		2725.8	12.8	125.9	mCAD/GW	25	0.85	(Moret et al., 2017)
Gasification to ethanol 61.8 MMGPY/mixed alcohol 76.2 MMGPY	Gasification/mixed alcohol	*	*	*	*	*				Cellulosic bioethanol	0.47		43.1	4.9		mCAD/PJ	20	0.96	(Phillips et al., 2007 ; Wright et Brown, 2019)
Gasification. Bio. CCS. Hydrogen	Gasification/Hydrogen	*	*	*	*	*				Hydrogen	0.43		2921.3	54.3	172.1	mCAD/GW	25	0.86	(Moret et al., 2017 ; Tock, 2013)
Gasification. Methanol synthesis, Methanol to Gasoline (MTG) 49.6 MGPY	Gasification/methanol synthesis	*	*	*	*	*				Gasoline(bio), LPG(bio)	0.43		36.8	4.4	1.9	mCAD/PJ	20	0.96	(Phillips et al., 2011)
Liquefaction. Fermentation. Ethanol. Solvent. 1,4-Dioxane 39.4MGPY	Liquefaction & Fermentation	*	*	*	*	*			Electricity, Natural gas	Cellulosic bioethanol	0.21	0.51	131.7	9.6	11.0	mCAD/PJ	30	0.91	(Li et al., 2018)
Liquefaction. Fermentation. Ethanol. Solvent. Acetone 34.8MGPY	Liquefaction & Fermentation	*	*	*	*	*			Electricity, Natural gas	Cellulosic bioethanol	0.17	1.44	142.2	12.3	14.1	mCAD/PJ	30	0.91	(Li et al., 2018)
Liquefaction. Fermentation. Ethanol. Solvent. GVL 50.6MGPY	Liquefaction & Fermentation	*	*	*	*	*				Cellulosic bioethanol	0.28		102.2	5.3	6.1	mCAD/PJ	30	0.91	(Li et al., 2018 ; Han et al., 2015)
Liquefaction. Fermentation. Ethanol. Solvent. THF 53.3MGPY	Liquefaction & Fermentation	*	*	*	*	*			Electricity, Natural gas	Cellulosic bioethanol	0.25	1.09	96.2	6.9	7.9	mCAD/PJ	30	0.91	(Li et al., 2018)

Continued

Table A-I 1 Continued.

Technology	**Conversion process**	**Forest industry residues**	**Hogfuel**	**Chips**	**Firewood**	**Slash**	**Pulp and paper waste**	**Spent liquor**	**Energy input**	**Bioenergy**	**EFF (Out/Input)**	**CEFF (Input fuel/Out)**	**Investment cost**	**Fixed operating cost**	**Variable operating cost**	**Cost unit**	**Life Time**	**Availability factor**	**Reference**
Pellet. Production. Forest residue. Regular 190kt	Pelletizing	*		*	*	*			Electricity, Natural gas	Pellets	0.72	0.04	13.3	0.6	2.2	mCAD/PJ	30	0.85	(Shahrukh et al., 2016)
Pellet. Production. Forest residue. Steam pretreated 290kt	Pelletizing	*		*	*	*			Electricity, Natural gas	Pellets	0.51	0.04	24.6	0.6	2.7	mCAD/PJ	30	0.85	(Shahrukh et al., 2016)
Pyrolysis. Wood 10MW	Pyrolysis	*	*	*	*	*				Pyrolysis oil	0.68		1518.3	18.2	57.7	mCAD/GW	25	0.85	(Moret et al., 2017)
CHP ORC system. Wet/dry wood 2.08MWe	CHP/ORC/Wet/dry	*	*	*	*	*	*	*		Electricity, Heat	0.85		2095.1	55.7	176.4	mCAD/GW	25	0.91	(Moret et al., 2016)
CHP. biomass combustion. ORC 2.5MW	CHP/ORC	*	*	*	*	*	*	*		Electricity, Heat	0.89		656.0	5.5	17.4	mCAD/GW	20	0.91	(Rentizelas et al., 2009)
CHP. biomass gasification. IC engine 3MW	CHP/Gasification/IC engine	*	*	*	*	*	*	*		Electricity, Heat	0.81		1155.6	16.6	52.7	mCAD/GW	20	0.91	(Rentizelas et al., 2009)
CHP. District. Wood 20MWth	CHP/District	*	*	*	*	*	*			Heat, Electricity	0.71		933.1	9.8	25.1	mCAD/GW	25	0.85	(Moret et al., 2017)
CHP. Industry. Wood 20MWth	CHP/Industry	*	*	*	*	*	*	*		Heat, Electricity	0.71		933.1	9.8	25.1	mCAD/GW	25	0.85	(Moret et al., 2017)
Boiler. Decentralized. Wood. 0.1MW	Boiler/Decentralized	*	*	*	*	*	*			Heat	0.85		535.1	5.2	13.5	mCAD/GW	17	0.29	(Moret et al., 2017)

Continued

Table A-I 1 Continued.

Technology	Conversion process	Forest industry residues	Hogfuel	Chips	Firewood	Slash	Pulp and paper waste	Spent liquor	Energy input	Bioenergy	EFF (Out/Input)	CEFF (Input fuel/Out)	Investment cost	Fixed operating cost	Variable operating cost	Cost unit	Life Time	Availability factor	Reference
Boiler. District. Wood.10MW	Boiler/District	*	*	*	*	*	*	*		Heat	0.864		133.2	0.7	1.9	mCAD/GW	17	0.9	(Moret et al., 2017)
Boiler. Industry. Wood.10MW	Boiler/Industry	*	*	*	*	*	*	*		Heat	0.927		133.2	0.7	1.9	mCAD/GW	17	0.9	(Moret et al., 2017)
Boilers. Industrial. Wood	Boilers/Industrial	*	*	*	*	*	*	*		Heat	0.59		73.8	0.6	1.6	mCAD/GW	15	0.9	(Panos et Kannan, 2016)
Boilers. Residential. Wood. High	Boilers/Residential			*	*	*				Heat	0.72		1628.0	1.9	4.9	mCAD/GW	15	0.9	(Panos et Kannan, 2016)
Boilers. Residential. Wood. Low	Boilers/Residential			*	*	*				Heat	0.72		505.6	0.6	1.6	mCAD/GW	15	0.9	(Panos et Kannan, 2016)
Boilers. Services. Wood	Boilers/Services	*	*	*	*	*	*	*		Heat	0.72		171.9	0.9	2.3	mCAD/GW	15	0.9	(Panos et Kannan, 2016)

Table A-I 2 The techno-economic data of secondary forest-based bioenergy technologies.

Technology	**Conversion process**	**Feedstock**	**Energy input**	**Bioenergy**	**EFF (Out/Input)**	**CEFF (Input fuel/Out)**	**Investment cost**	**Fixed operating cost**	**Variable operating cost**	**Cost unit**	**Life Time**	**Availability factor**	**Reference**
CH4 reforming. CCS. Hydrogen	CH4 reforming/Hydrogen	Syngas		Hydrogen	0.73		788.55	17.89	56.64	mCAD/GW	25	0.86	(Moret et al., 2017 ; Tock, 2013)
Electrolysis. Hydrogen	Electrolysis/Hydrogen	Syngas	Electricity	Hydrogen	0.85	1.18	356.36	8.55	27.08	mCAD/GW	15	0.90	(Moret et al., 2017 ; Gassner et Maréchal,
CHP. Combined-Cycle Gas Turbine CCGT. SNG 34-55MWe	CHP/CCGT	Syngas		Electricity, Heat	0.88		897.65	15.91	50.39	mCAD/GW	25	0.91	(Moret et al., 2016)
CHP. Oil/Bio-Oil 0.2-2MWe	CHP/BioOil	Pyrolysis oil		Electricity, Heat	0.82		568.29	15.76	49.94	mCAD/GW	20	0.91	(Moret et al., 2016)
Boilers. Industrial. Oil	Boilers/Industrial	Pyrolysis oil		Heat	0.77		33.37	0.30	0.78	mCAD/GW	15	0.90	(Panos et Kannan, 2016)
Boilers. Industrial. Pellet	Boilers/Industrial	Pellets		Heat	0.74		75.84	0.61	1.56	mCAD/GW	15	0.90	(Panos et Kannan, 2016)
Boilers. Residential. Oil. High	Boilers/Residential	Pyrolysis oil		Heat	0.83		1365.13	1.62	4.16	mCAD/GW	15	0.90	(Panos et Kannan, 2016)
Boilers. Residential. Oil. Low	Boilers/Residential	Pyrolysis oil		Heat	0.83		414.59	0.51	1.30	mCAD/GW	15	0.90	(Panos et Kannan, 2016)
Boilers. Residential. Pellet. High	Boilers/Residential	Pellets		Heat	0.90		2386.45	7.18	18.45	mCAD/GW	15	0.90	(Panos et Kannan, 2016)
Boilers. Residential. Pellet. Low	Boilers/Residential	Pellets		Heat	0.90		637.06	1.92	4.94	mCAD/GW	15	0.90	(Panos et Kannan, 2016)
Boilers. Services. Oil	Boilers/Services	Pyrolysis oil		Heat	0.83		110.22	0.61	1.56	mCAD/GW	15	0.90	(Panos et Kannan, 2016)
Boilers. Services. Pellet	Boilers/Services	Pellets		Heat	0.90		232.58	1.42	3.64	mCAD/GW	15	0.90	(Panos et Kannan, 2016)

Part B

Hydrothermal liquefaction (HTL) produces a liquid fuel known as biocrude, comparable to crude oil. It can be upgraded to the whole distillate range of petroleum-derived fuel products (conventional hydrocarbon fuel) via hydrotreating and hydrocracking. The upgraded hydrocarbon fuel is stabilized through cooling and distillation to generate gasoline, diesel, and heavy oil fractions following their boiling point ranges (Elliott *et al.*, 2015 ; Zhu *et al.*, 2014). Bio-methanol, also known as methyl alcohol or wood alcohol usable either as a blend in fuel in internal combustion engines or in fuel cell vehicles. Methanol is considered as a functional product in the chemical industry as a starting point for many chemicals. Lignocellulosic-based bio-methanol could be a feasible way to address several of the problems related to the current use of petroleum-derived fuels, such as energy security and GHG emissions (Hamelinck et Faaij, 2002). Additionally, bio-methanol production via synthesis gas from biomass is similar to coal-based methanol. Crude bio-methanol produced by removing the last distillation step (instead of grade AA methanol) is suitable for marine diesel fuel (Carvalho *et al.*, 2018).

Ethanol and butanol as fermentation products are compatible with spark-ignited engines. Ethanol derived from starch or sugar is identified as “first-generation” biofuel, and ethanol generated from lignocellulose is known as “second-generation” biofuel (Van Walsum et Wheeler, 2013). Today, bioethanol is recognized as one of the leading gasoline additives and an octane booster. First-generation bioethanol production is a well-known commercialized process. Whereas, lignocellulosic bioethanol attracts global attention because of reducing environmental burdens, high feedstock availability, feedstock capability to compete with the crude oil price, and potential to enhance food security (Li *et al.*, 2018). An essential preference for fermentation’s alcohol is that they are directly applicable as fuel without upgrading. For instance, ethanol is blended into gasoline at up to 10 % in North America. The flex-fuel vehicles that are available now can work with ethanol blended into gasoline up to 85%. Cellulosic ethanol is a distinguished substitution for petroleum gasoline that may not jeopardize food security. It has low energy efficiency (HHV: 29.7 MJ/kg) and is not currently cost-effective. Contrary to ethanol, a non-fungible fuel, butanol (HHV: 36.0 MJ/kg) can blend with gasoline in any percentage. Upgrading the fermentation process output through catalytic hydrolysis and injecting hydrogen would make advanced biofuels known as hydrocarbons (HC's). The optimal HC's could be used as "drop-in" fuel, although conversion cost is currently very high as the technology is under development (Van Walsum et Wheeler, 2013 ; Guo, Song et Buhain, 2015). Butanol is known as an "advanced" biofuel because it can be mixed at any ratio with gasoline. However, it is not considered a "drop-in" fuel since butanol energy density is lower than gasoline (Van Walsum et Wheeler, 2013). Biological conversion of hemicelluloses in existing Kraft pulp mills, which produce dissolving pulp, can result in butanol (bio) production. The biobutanol properties are similar to gasoline and better than bioethanol (higher energy content, less corrosive and volatile) (Levasseur *et al.*, 2017).

Fischer–Tropsch (FT) catalytic synthesis benefits from a long industrial experience. FT is compatible with current fuel infrastructure (Swanson *et al.*, 2010). FT-liquids are free of sulphur and contain very few aromatics compared to gasoline and diesel, which results in lower emission levels when applied in internal combustion engines (Tijmensen *et al.*, 2002).

Bio-oil derived through fast pyrolysis of lignocellulosic feedstock is the primary product for energy applications since it can substitute for crude oil in petroleum refineries. It is required to enhance the oil quality by decreasing oxygen and water content and rising energy density and shelf life. Upgrading pyrolysis oil to a usable transport fuel such as diesel, gasoline, and kerosene needs full deoxygenation and some conventional refining (Van Walsum et Wheeler, 2013 ; Li *et al.*, 2017).

The gasoline (bio) derived through the methanol-to-gasoline (MTG) process is similar to conventional gasoline. It is compatible with current infrastructure and automobiles, making it an advanced drop-in biofuel (Phillips *et al.*, 2011). Besides, liquefied petroleum gas (LPG) is a co-product of this conversion process.

Wood pellets are a densified form of biomass with less moisture content, higher energy equivalent, and more convenient transport and storage capabilities. Pellets emit a low amount of SO_2 and NO_x while having precise combustion (Guo, Song et Buhain, 2015 ; Shahrukh *et al.*, 2015).

Syngas's (SNG) energy density is about half of natural gas and is applicable in the steam cycles, gas engines, fuel cells, or turbines to generate power and heat. SNG plays an intermediate role in producing liquid fuels and other biochemicals, such as hydrogen, synthetic natural gas, naphtha, kerosene, diesel, methanol, dimethyl ether and ammonia. It can be converted into alcohols and/or hydrocarbons (HCs) employing fermentation or chemical catalytic methods (Ibarra-Gonzalez et Rong, 2018 ; Van Walsum et Wheeler, 2013).

Bio-based heat and electricity are generated by converting the chemical energy of biomass into heat/mechanical power/electricity by combustion, co-firing, combined heat and power (CHP) systems (McKendry, 2002).

APPENDIX II

SUPPORTING INFORMATION
IMPACT OF THE BIOGENIC CARBON NEUTRALITY ASSUMPTION FOR ACHIEVING A NET-ZERO EMISSION TARGET: INSIGHTS FROM A TECHNO-ECONOMIC ANALYSIS

Part A

A comprehensive set of techno-economic data of the forest-based bioenergy technologies (BIOF) is presented in Table A-II 1.

Table A-II 1 Techno-economic data of the forest-based bioenergy technologies (BIOF).

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.Butanol.Production.Fermentation.25	Fermentation	Natural gas	Cellulosic butanol, Heat	0.43	0.18	99.98	12.86	0.75	0.37	30	0.96	(Levasseur et al., 2017)
BIOF.Butanol.Production.Fermentation.25.CCS	Fermentation	Natural gas	Cellulosic butanol, Heat	0.28	0.59	10.00	22.65	1.33	0.58	30	0.96	(Levasseur et al., 2017 ; Berghout et al., 2015)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.THF.53.3MGPY	Liquefaction/fermentation	Electricity, Natural gas	Cellulosic ethanol	0.24	1.42	101.87	119.31	8.57	9.81	30	0.91	(Li et al., 2018)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.THF.53.3MGPY.CCS	Liquefaction/fermentation	Electricity, Natural gas	Cellulosic ethanol	0.22	1.83	10.19	129.25	9.16	10.03	30	0.91	(Li et al., 2018 ; Berghout et al., 2015)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.Acetone.34.8MGPY	Liquefaction/fermentation	Electricity, Natural gas	Cellulosic ethanol	0.17	1.74	76.54	176.36	15.29	17.51	30	0.91	(Li et al., 2018)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.Acetone.34.8MGPY.CCS	Liquefaction/fermentation	Electricity, Natural gas	Cellulosic ethanol	0.16	2.05	7.65	183.84	15.74	17.68	30	0.91	(Li et al., 2018 ; Berghout et al., 2015)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.1,4-Dioxane.39.4MGPY	Liquefaction/fermentation	Electricity, Natural gas	Cellulosic ethanol	0.20	1.34	101.87	163.36	11.95	13.68	30	0.91	(Li et al., 2018)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.1,4-Dioxane.39.4MGPY.CCS	Liquefaction/fermentation	Electricity, Natural gas	Cellulosic ethanol	0.19	1.75	10.19	173.30	12.54	13.90	30	0.91	(Li et al., 2018 ; Berghout et al., 2015)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.GVL.50.6MGPY	Liquefaction/fermentation		Cellulosic ethanol	0.35	0.00	111.98	126.78	6.56	7.51	30	0.91	(Li et al., 2018 ; Han et al., 2015)
BIOF.Cellulosic ethanol.Liquefaction.Fermentation.Solvent.GVL.50.6MGPY.CCS	Liquefaction/fermentation		Cellulosic ethanol	0.26	0.00	11.20	137.69	7.21	7.75	30	0.91	(Han et al., 2015 ; Li et al., 2018 ; Berghout et al., 2015)

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.Cellulosic ethanol.Fermentation.Ethanol.Enzyme.Dilute-acid.53.4MGPY	Fermentation		Cellulosic ethanol, electricity	0.37	0.00	111.98	108.55	5.99	15.58	20	0.91	(Kazi et al., 2010 ; Li et al., 2018)
BIOF.Cellulosic ethanol.Fermentation.Ethanol.Enzyme.Dilute-acid.53.4MGPY.CCS	Fermentation		Cellulosic ethanol, electricity	0.27	0.00	11.20	119.47	6.64	15.82	20	0.91	(Berghout et al., 2015 ; Kazi et al., 2010 ; Li et al., 2018)
BIOF.Cellulosic ethanol.Fermentation.Enzyme.NREL.61 MGPY	Fermentation		Cellulosic ethanol	0.43	0.00	111.98	106.78	6.09	6.98	20	0.91	(Humbird et al., 2011 ; Li et al., 2018)
BIOF.Cellulosic ethanol.Fermentation.Enzyme.NREL.61 MGPY.CCS	Fermentation		Cellulosic ethanol	0.30	0.00	11.20	117.69	6.74	7.22	20	0.91	(Humbird et al., 2011 ; Li et al., 2018 ; Berghout et al., 2015)
BIOF.Bio oil.Renewable diesel.Fast pyrolysis and hydroprocessing 57.6 MGPY	Fast pyrolysis	Electricity, Natural gas	Bio crude oil, renewable	0.55	0.27	34.43	72.60	5.15	4.60	30	0.91	(Wright et Brown, 2019 ; Li et al., 2017)
BIOF.Bio oil.Renewable diesel.Fast pyrolysis and hydroprocessing 57.6 MGPY.CCS	Fast pyrolysis	Electricity, Natural gas	Bio crude oil, renewable	0.51	0.41	3.44	75.96	5.35	4.67	30	0.91	(Berghout et al., 2015 ; Wright et Brown, 2019 ; Li et al., 2017)
BIOF.Butanol.HTL and upgrading system 69.9 MGGEPY	Hydrothermal liquefaction	Electricity, Natural gas	Cellulosic butanol	0.66	0.12	78.78	69.80	6.64	5.11	20	0.91	(Zhu et al., 2014)
BIOF.Butanol.HTL and upgrading system 69.9 MGGEPY.CCS	Hydrothermal liquefaction	Electricity, Natural gas	Cellulosic butanol	0.54	0.44	7.88	77.48	7.09	5.28	20	0.91	(Berghout et al., 2015 ; Zhu et al., 2014)
BIOF.CHP.biomass combustion.ORC.2.5MW	CHP/ORC		Electricity, Heat	0.89	0.00	83.83	25.79	0.22	0.69	20	0.91	(Rentizelas et al., 2009)
BIOF.CHP.biomass combustion.ORC.2.5MW.CCS	CHP/ORC		Electricity, Heat	0.53	0.00	8.38	35.29	0.75	0.87	20	0.91	(Berghout et al., 2015 ; Rentizelas et al., 2009)

Continued

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.CHP.biomass gasification.IC engine.3MW	CHP/Gasification/IC engine		Electricity, Heat	0.81	0.00	83.83	45.44	0.65	2.07	20	0.91	(Rentizelas et al., 2009)
BIOF.CHP.biomass gasification.IC engine.3MW.CCS	CHP/Gasification/IC engine		Electricity, Heat	0.50	0.00	8.38	54.69	1.18	2.25	20	0.91	(Berghout et al., 2015 ; Rentizelas et al., 2009)
BIOF.Cellulosic ethanol.Gassifcation.61.8 MMGPY/mixed alcohol 76.2 MMGPY	Gasification/mixed alcohol		Cellulosic ethanol	0.47	0.00	231.69	53.41	6.05	0.00	20	0.96	(Wright et Brown, 2019 ; Phillips et al., 2007)
BIOF.Cellulosic ethanol.Gassifcation.61.8 MMGPY/mixed alcohol 76.2	Gasification/mixed alcohol		Cellulosic ethanol	0.24	0.00	23.17	75.97	7.39	0.00	20	0.96	(Berghout et al., 2015 ; Wright et Brown, 2019 ; Phillips et al., 2007)
BIOF.Bio oil.Gassification.Methanol synthesis, Methanol to Gasoline 49.6 MGPY	Gasification/methanol synthesis		Bio cude oil, cellulosic	0.47	0.00	231.69	45.57	5.43	2.32	20	0.96	(Phillips et al., 2011)
BIOF.Bio oil.Gassification.Methanol synthesis, Methanol to Gasoline 49.6 MGPY.CCS	Gasification/methanol synthesis		Bio cude oil, cellulosic	0.24	0.00	23.17	68.13	6.77	2.82	20	0.96	(Berghout et al., 2015 ; Phillips et al., 2011)
BIOF.Pyrolysis oil.Pyrolysis.Wood.10MW	Pyrolysis		Pyrolysis oil	0.68	0.00	51.65	59.70	0.72	2.27	25	0.85	(Moret et al., 2017)
BIOF.Pyrolysis oil.Pyrolysis.Wood.10MW.CCS	Pyrolysis		Pyrolysis oil	0.52	0.00	5.17	65.07	1.03	2.38	25	0.85	(Berghout et al., 2015 ; Moret et al., 2017)
BIOF.Syngas.Gasification.Wood.20MW	Gasification		Syngas	0.86	0.00	231.69	107.18	0.50	4.95	25	0.85	(Moret et al., 2017)
BIOF.Syngas.Gasification.Wood.20MW.CCS	Gasification		Syngas	0.30	0.00	23.17	129.87	1.85	5.45	25	0.85	(Berghout et al., 2015 ; Moret et al., 2017)

Continued

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.H2.Hydrogen.Electrolysis	Electrolysis/Hydrogen	Electricity	Hydrogen	0.85	1.18	49.35	14.01	0.34	1.06	15	0.90	(Moret et al., 2017 ; Gassner et Maréchal, 2008)
BIOF.H2.Hydrogen.CH4 reforming	CH4 reforming/Hydrogen		Hydrogen	0.73	0.00	69.99	31.01	0.70	2.23	25	0.86	(Berghout et al., 2015 ; Tock, 2013)
BIOF.H2.Hydrogen.CH4 reforming.CCS	CH4 reforming/Hydrogen		Hydrogen	0.50	0.00	7.00	38.17	1.12	2.38	25	0.86	(Berghout et al., 2015 ; Moret et al., 2017 ; Tock, 2013)
BIOF.CHP.Industry.Wood.20MWth	CHP/Industry		Electricity, Heat	0.71	0.00	83.83	36.69	0.38	0.99	25	0.85	(Moret et al., 2017)
BIOF.CHP.Industry.Wood.20MWth.CCS	CHP/Industry		Electricity, Heat	0.46	0.00	8.38	44.98	0.88	1.17	25	0.85	(Berghout et al., 2015 ; Moret et al., 2017)
BIOF.CHP.District.Wood.20MWth	CHP/District		Electricity, Heat	0.71	0.00	83.83	36.69	0.38	0.99	25	0.85	(Moret et al., 2017)
BIOF.CHP.District.Wood.20MWth.CCS	CHP/District		Electricity, Heat	0.46	0.00	8.38	44.98	0.88	1.17	25	0.85	(Berghout et al., 2015 ; Moret et al., 2017)
BIOF.CHP.Combined-Cycle Gas Turbine CCGT.Syngas.34-55MWe	CHP/CCGT		Electricity, Heat	0.88	0.00	49.35	35.30	0.63	1.98	25	0.91	(Moret et al., 2016)
BIOF.CHP.Combined-Cycle Gas Turbine CCGT.Syngas.34-55MWe.CCS	CHP/CCGT		Electricity, Heat	0.63	0.00	4.94	40.13	0.91	2.09	25	0.91	(Berghout et al., 2015 ; Moret et al., 2016)
BIOF.CHP.Pyrolysis oil.0.2-2MWe	CHP/BioOil		Electricity, Heat	0.82	0.00	69.99	22.35	0.62	1.96	20	0.91	(Moret et al., 2016)

Continued

Table A-II 1 Continued.

Technology	**Conversion process**	**Energy input**	**Bioenergy**	**EFF**[1]	**CEFF**[2]	**GHGs**[3]	**Investment cost**[4]	**Fixed operating cost**[5]	**Variable operating cost**[5]	**Life Time**[6]	**Availability factor**	**Reference**
BIOF.CHP.Pyrolysis oil.0.2-2MWe.CCS	CHP/BioOil		Electricity, Heat	0.54	0.00	7.00	29.94	1.06	2.11	20	0.91	(Berghout et al., 2015 ; Moret et al., 2016)
BIOF.CHP.ORC system.Wet.Dry.wood.2.08MWe	CHP/ORC/Wet/dry		Electricity, Heat	0.85	0.00	83.83	82.38	2.19	6.94	25	0.91	(Moret et al., 2016)
BIOF.CHP.ORC system.Wet.Dry.wood.2.08MWe.CCS	CHP/ORC/Wet/dry		Electricity, Heat	0.51	0.00	8.38	91.20	2.70	7.12	25	0.91	(Berghout et al., 2015 ; Moret et al., 2016)
BIOF.Boiler.Industry.Wood.10MW	Boiler/Industry		Heat	0.93	0.00	83.83	5.24	0.03	0.08	17	0.90	(Moret et al., 2017)
BIOF.Boiler.Industry.Wood.10MW.CCS	Boiler/Industry		Heat	0.54	0.00	8.38	13.73	0.53	0.26	17	0.90	(Berghout et al., 2015 ; Moret et al., 2017)
BIOF.Boiler.District.Wood.10MW	Boiler/District		Heat	0.86	0.00	83.83	5.24	0.03	0.08	17	0.90	(Moret et al., 2017)
BIOF.Boiler.District.Wood.10MW.CCS	Boiler/District		Heat	0.52	0.00	8.38	13.73	0.53	0.26	17	0.90	(Berghout et al., 2015 ; Moret et al., 2017)
BIOF.Boiler.Decentralized.Wood.0.1MW	Boiler/Decentralized		Heat	0.85	0.00	83.83	21.04	0.21	0.53	17	0.29	(Moret et al., 2017)
BIOF.Boiler.Decentralized.Wood.0.1MW.CCS	Boiler/Decentralized		Heat	0.51	0.00	8.38	1093.51	41.14	0.71	17	0.29	(Berghout et al., 2015 ; Moret et al., 2017)
BIOF.Syngas.Gasification facility.gasifier+methanisation	Gasification/methanation		Syngas, Electricity	0.55	0.00	231.69	139.16	1.59	4.64	20	0.96	(Panos et Kannan, 2016)

Continued

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.Syngas.Gasification facility.gasifier+methanisation.CCS	Gasification/methanation		Syngas, Electricity	0.25	0.00	23.17	161.76	2.94	5.14	20	0.96	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Syngas.Gasification facility.gasifier+mechanization elctrolyser	Gasification/methanation	Electricity	Syngas	0.54	0.85	138.46	169.78	2.26	6.59	20	0.96	(Panos et Kannan, 2016)
BIOF.Syngas.Gasification facility.gasifier+methanisation.elctrolyser.CCS	Gasification/methanation	Electricity	Syngas	0.27	0.95	13.85	183.31	3.06	6.89	20	0.96	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Pellet.Densification.Forest residue.Regular.190kt	Densification	Electricity, Natural gas	Wood pellet	0.87	0.04	10.05	16.53	0.78	2.70	30	0.85	(Shahrukh et al., 2016)
BIOF.Pellet.Densification.Forest residue.Regular.190kt.CCS	Densification	Electricity, Natural gas	Wood pellet	0.84	0.09	1.01	17.53	0.84	2.72	30	0.85	(Berghout et al., 2015 ; Shahrukh et al., 2016)
BIOF.Pellet.Densification.Forest residue.Steam pretreated.290kt	Densification	Electricity, Natural gas	Wood pellet	0.88	0.04	9.90	30.56	0.79	3.33	30	0.85	(Shahrukh et al., 2016)
BIOF.Pellet.Densification.Forest residue.Steam pretreated.290kt.CCS	Densification	Electricity, Natural gas	Wood pellet	0.85	0.08	0.99	31.54	0.85	3.35	30	0.85	(Berghout et al., 2015 ; Shahrukh et al., 2016)
BIOF.FT Diesel.catalytic hydroprocessing.high temperature.flow gasifier.41.7MGPY	Gasification/Fischer-Tropsch		FT diesel, Electricity	0.53	0.00	231.69	148.42	3.43	2.94	20	0.91	(Swanson et al., 2010)
BIOF.FT Diesel.catalytic hydroprocessing high temperature.flow gasifier.41.7MGPY.CCS	Gasification/Fischer-Tropsch		FT diesel, Electricity	0.25	0.00	23.17	170.98	4.77	3.44	20	0.91	(Berghout et al., 2015 ; Swanson et al., 2010)
BIOF.FT Diesel catalytic hydroprocessing low temperature fluidized bed gasifie.32.3MGPY	Gasification/Fischer-Tropsch		FT diesel, Electricity	0.43	0.00	231.69	151.58	3.65	3.96	20	0.91	(Swanson et al., 2010)

Continued

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.FT Diesel.catalytic hydroprocessing.low temperature. luidized bed gasifie.32.3MGPY.CCS	Gasification/Fischer-Tropsch		FT diesel, Electricity	0.22	0.00	23.17	174.15	5.00	4.46	20	0.91	(Berghout et al., 2015 ; Swanson et al., 2010)
BIOF.Boilers.Industrial.Oil	Boilers/Industrial		Heat	0.77	0.00	69.99	1.31	0.01	0.03	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Industrial.Oil.CCS	Boilers/Industrial		Heat	0.52	0.00	7.00	8.46	0.43	0.18	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Services.Oil	Boilers/Services		Heat	0.83	0.00	69.99	4.33	0.02	0.06	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Services.Oil.CCS	Boilers/Services		Heat	0.54	0.00	7.00	11.48	0.44	0.21	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Residential.Oil.Low	Boilers/Residential		Heat	0.83	0.00	69.99	16.30	0.02	0.05	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Residential.Oil.Low.CCS	Boilers/Residential		Heat	0.54	0.00	7.00	360.14	13.23	0.20	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Residential.Oil.High	Boilers/Residential		Heat	0.83	0.00	69.99	53.68	0.06	0.16	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Residential.Oil.High.CCS	Boilers/Residential		Heat	0.54	0.00	7.00	63.86	0.60	0.31	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Industrial.Pellet	Boilers/Industrial		Heat	0.74	0.00	87.80	2.98	0.02	0.06	15	0.90	(Panos et Kannan, 2016)

Continued

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.Boilers.Industrial.Pellet.CCS	Boilers/Industrial		Heat	0.46	0.00	8.78	11.86	0.55	0.25	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Services.Pellet	Boilers/Services		Heat	0.90	0.00	87.80	9.14	0.06	0.14	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Services.Pellet.CCS	Boilers/Services		Heat	0.52	0.00	8.78	18.02	0.58	0.33	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Residential.Pellet.Low	Boilers/Residential		Heat	0.90	0.00	87.80	25.05	0.08	0.19	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Residential.Pellet.Low.CCS	Boilers/Residential		Heat	0.52	0.00	8.78	370.62	13.39	0.38	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Residential.Pellet.High	Boilers/Residential		Heat	0.90	0.00	87.80	93.84	0.28	0.73	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Residential.Pellet.High.CCS	Boilers/Residential		Heat	0.52	0.00	8.78	105.75	0.92	0.91	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Industrial.Wood	Boilers/Industrial		Heat	0.59	0.00	83.83	2.90	0.02	0.06	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Industrial.Wood.CCS	Boilers/Industrial		Heat	0.41	0.00	8.38	11.40	0.52	0.24	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Services.Wood	Boilers/Services		Heat	0.72	0.00	83.83	6.76	0.04	0.09	15	0.90	(Panos et Kannan, 2016)

Continued

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.Boilers.Services.Wood.CCS	Boilers/Services		Heat	0.46	0.00	8.38	15.25	0.53	0.27	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Residential.Wood.Low	Boilers/Residential		Heat	0.72	0.00	83.83	19.88	0.02	0.06	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Residential.Wood.Low.CCS	Boilers/Residential		Heat	0.46	0.00	8.38	365.07	13.32	0.24	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Boilers.Residential.Wood.High	Boilers/Residential		Heat	0.72	0.00	83.83	64.01	0.08	0.19	15	0.90	(Panos et Kannan, 2016)
BIOF.Boilers.Residential.Wood.High.CCS	Boilers/Residential		Heat	0.46	0.00	8.38	75.54	0.69	0.37	15	0.90	(Berghout et al., 2015 ; Panos et Kannan, 2016)
BIOF.Methanol.grade AA.CoGasification.black liquor.crude glycerol	Co-Gasification	Electricity	Biomethanol	0.66	0.19	99.98	165.61	1.97	7.29	20	0.97	(Carvalho et al., 2018)
BIOF.Methanol.grade AA.CoGasification.black liquor.crude glycerol.CCS	Co-Gasification	Electricity	Biomethanol	0.49	0.26	10.00	175.34	2.55	7.51	20	0.97	(Berghout et al., 2015 ; Carvalho et al., 2018)
BIOF.Methanol.grade AA.CoGasification.black liquor	Co-Gasification	Electricity	Biomethanol	0.57	0.29	99.98	299.67	19.71	51.26	20	0.97	(Berghout et al., 2015 ; Carvalho et al., 2018)
BIOF.Methanol.grade AA.CoGasification.black liquor.CCS	Co-Gasification	Electricity	Biomethanol	0.61	0.36	10.00	309.41	20.29	51.47	20	0.97	(Berghout et al., 2015 ; Carvalho et al., 2018)
BIOF.H2.Hydrogen.BM Eimp.Gassification	Gasification/Hydrogen	Electricity	Hydrogen	0.61	0.06	138.46	53.03	6.26	19.20	25	0.86	(Tock, 2013)

Continued

Table A-II 1 Continued.

Technology	Conversion process	Energy input	Bioenergy	EFF[1]	CEFF[2]	GHGs[3]	Investment cost[4]	Fixed operating cost[5]	Variable operating cost[5]	Life Time[6]	Availability factor	Reference
BIOF.H2.Hydrogen.BM Self Gassification.MVR.PreCombustion	Gasification/Hydrogen		Hydrogen	0.43	0.00	149.00	129.82	10.06	25.04	25	0.86	(Tock, 2013)
BIOF.H2.Hydrogen.BM Eimp Gasification.MVR.PreCombustion CCS	Gasification/Hydrogen	Electricity	Hydrogen	0.60	0.28	90.00	81.93	6.26	27.90	25	0.86	(Tock, 2013)
BIOF.H2.Hydrogen.BM Eimp Gassification.PreCombustion CCS	Gasification/Hydrogen	Electricity	Hydrogen	0.47	0.23	90.00	93.74	7.61	30.51	25	0.86	(Tock, 2013)

[1] Output/Input
[2] Input fuel/Output
[3] Kt CO_2-eq/PJ
[4] MCAD2016/PJ
[5] MCAD2016/PJ
[6] Year

Part B

The following document provides supportive information for the original article, including detailed figures and additional results.

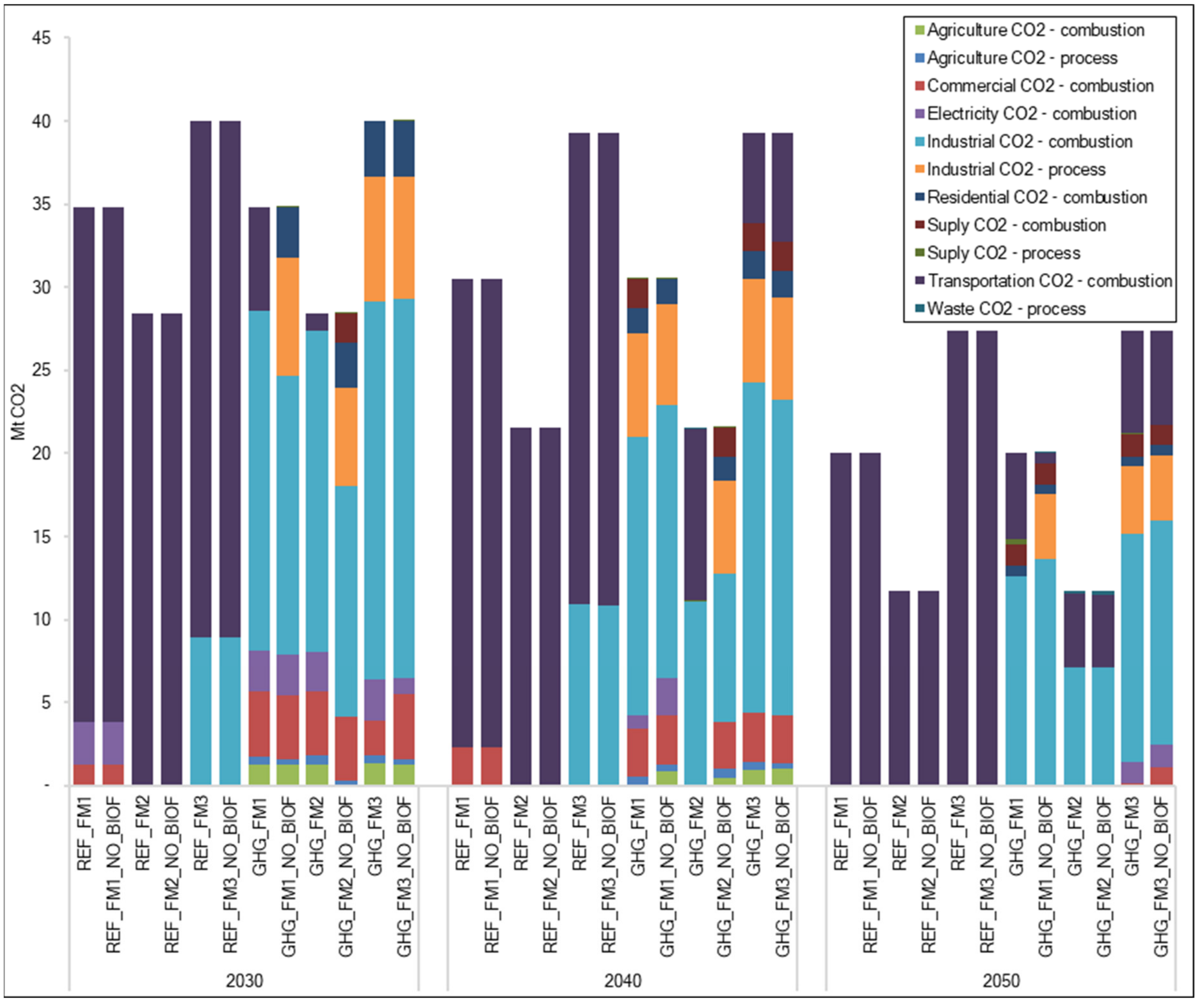


Figure A-II 1 Allocation of negative emissions obtained from forest sequestration to different sectors

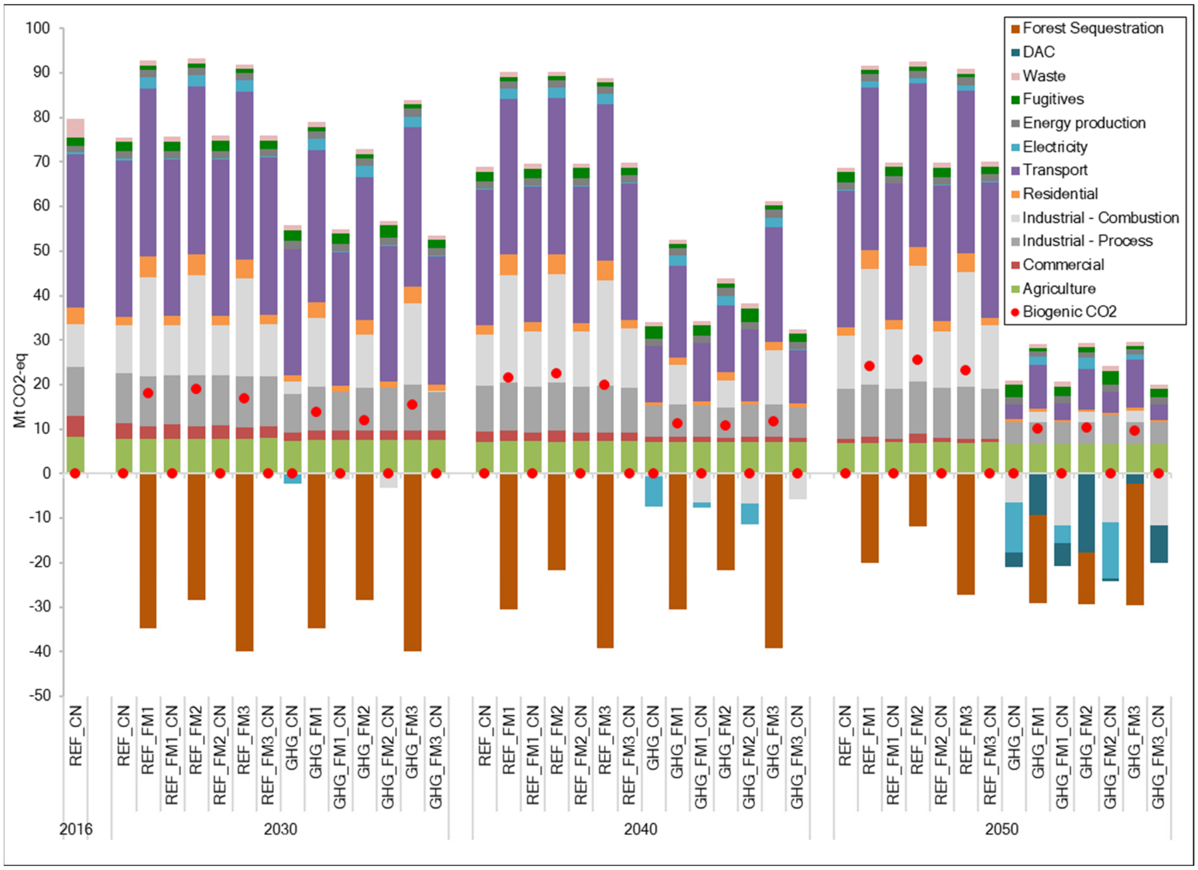


Figure A-II 2 Total annual GHG emission and CDR by sector in Quebec – carbon neutrality scenarios

We have shown the impact of BIOF in Figure A-II 3. Reliance on DAC increases slightly in scenarios without BIOF (GHG_FM1_NO_BIOF, GHG_FM2_NO_BIOF), except for GHG_FM3_NO_BIOF, where it decreases. CHP.ORC.CCS technology is a predominant BIOF process used to address the demand for heat and electricity for DAC. Excluding CHP.ORC.CCS forced the model to rely on alternative technologies to generate the required energy for DAC, increasing total costs and GHG emissions. Whereas GHG_FM3 has a high sequestration capacity and does not require a significant amount of DAC to sequester CO_2 emissions. It is simply a matter of lowering total costs by using BIOF for GHG_FM3.

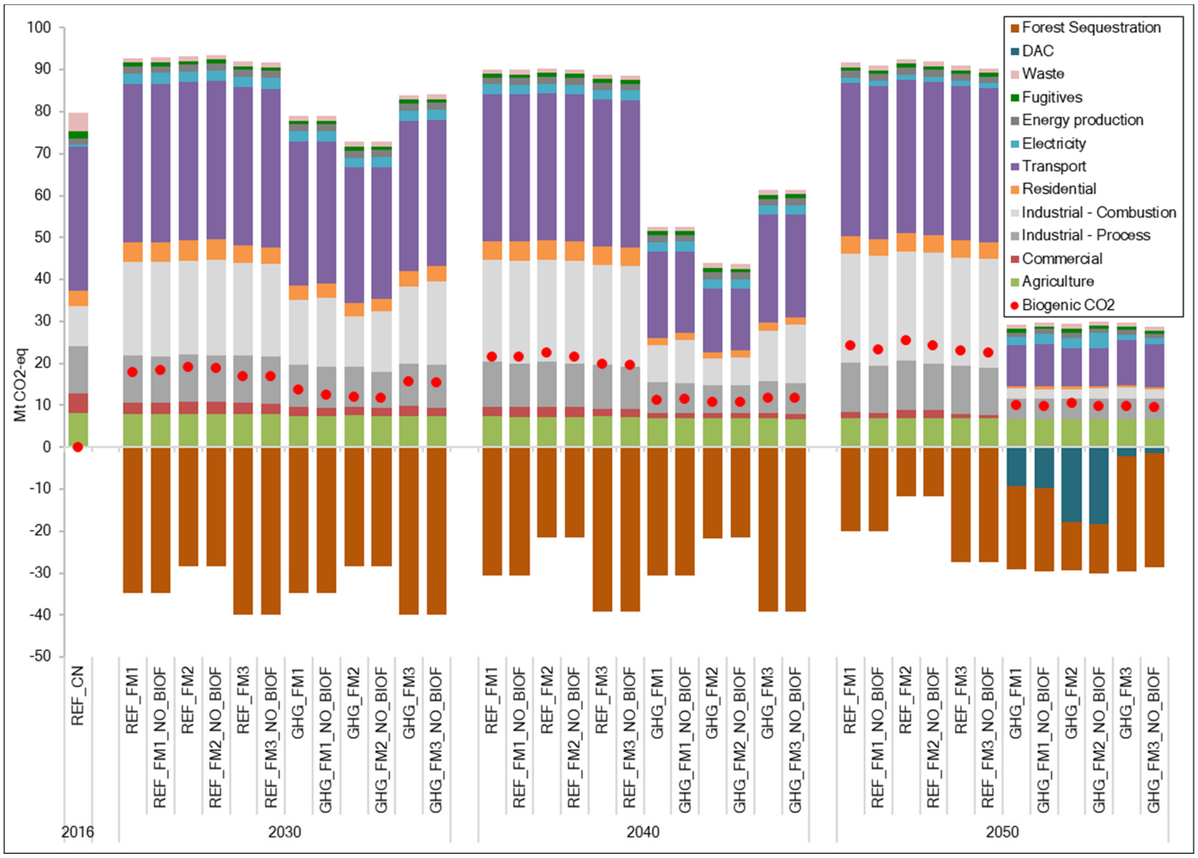


Figure A-II 3 Total annual GHG emission and CDR by sector in Quebec when excluding BIOF technologies

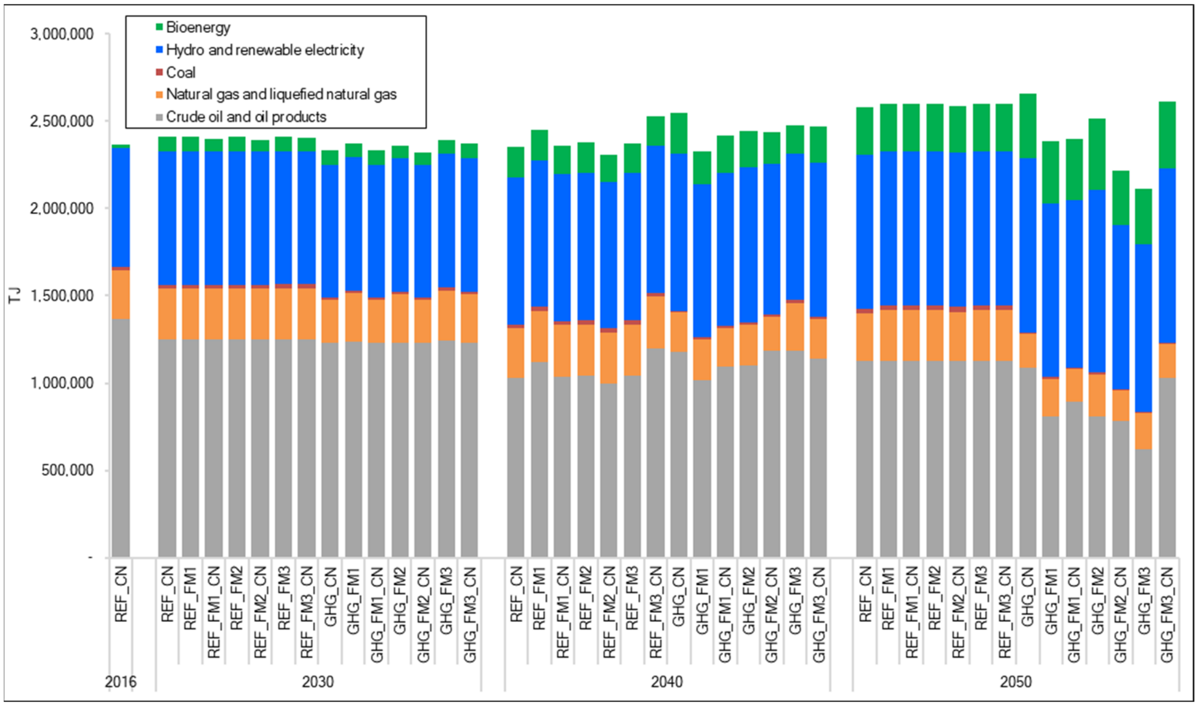


Figure A-II 4 Primary energy consumption in Quebec

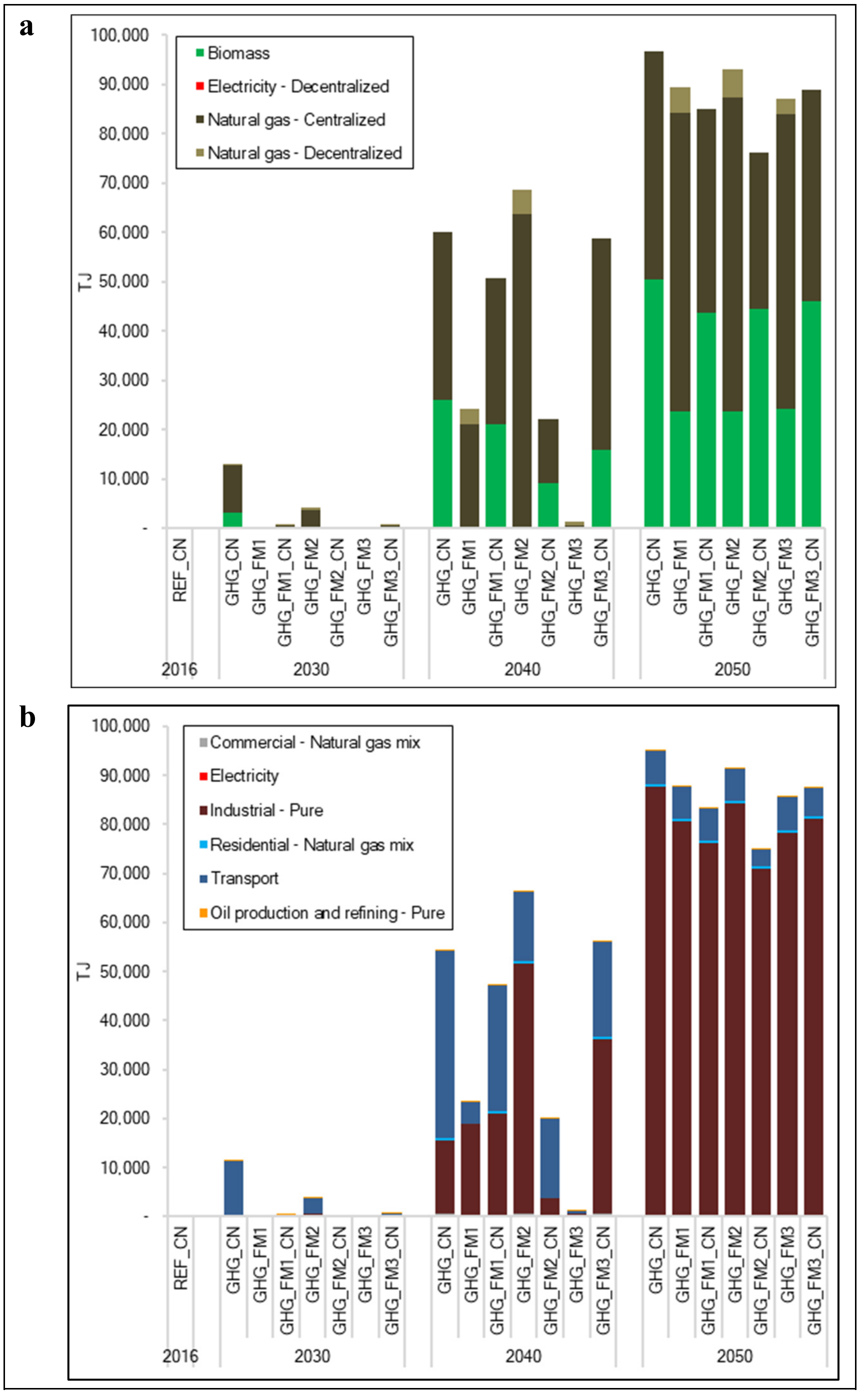


Figure A-II 5 (a) Hydrogen production in Quebec, (b) hydrogen consumption by sector in Quebec

GHG_FM3 uses no wood pellets while other GHG_FMx scenarios use nearly 10 PJ of wood pellets and GHG_FMx_CN scenarios use around 13 PJ of wood pellets.

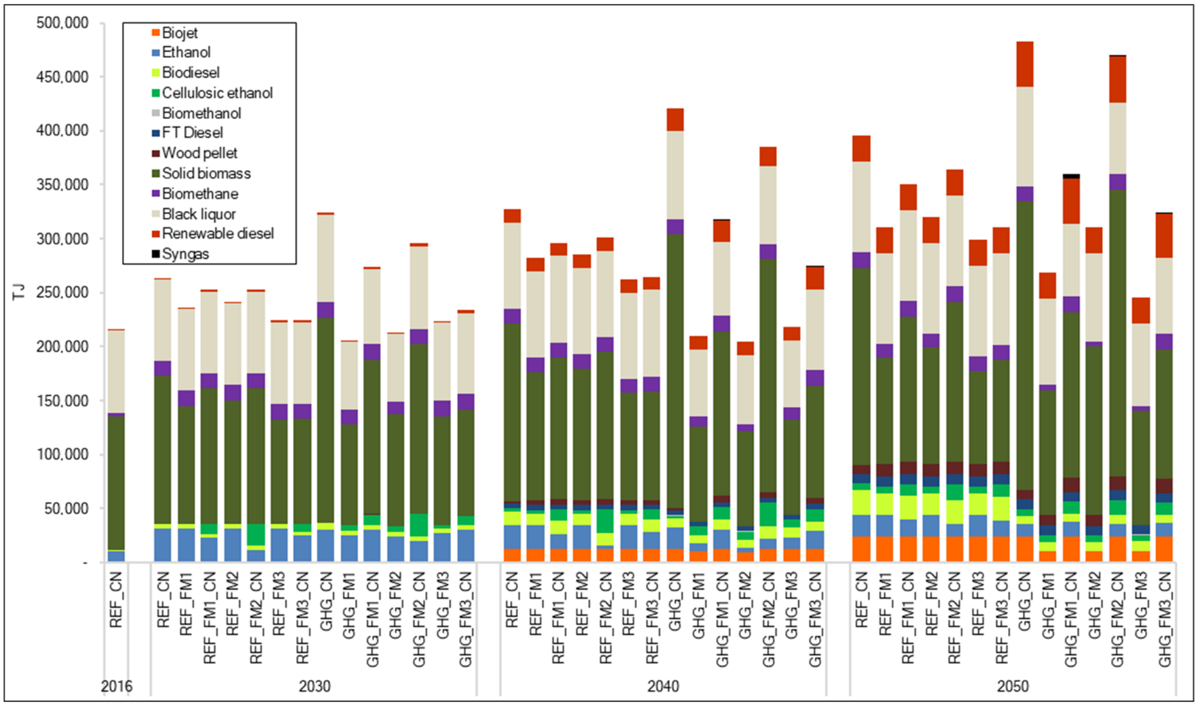


Figure A-II 6 The effect of forest management strategies and carbon neutrality on bioenergy consumption

Syngas with electricity and heat as co-products from gasification conversion process with CCS are utilized in GHG_FMx_CN scenarios (Figure A-II 7). In 2050, syngas is used mainly in different industrial processes as an alternative fuel for natural gas. It is also used in the electricity and transportation sectors within the GHG_FM1_CN scenario (after 2045) to meet the demand with a carbon neutral bioenergy source. CHP/ORC technology with CCS produces the required heat and electricity for GHG scenarios of FM2 (high feedstock availability) from 2040 and other GHG scenarios from 2050. CHP/ORC technology with CCS provides the heat for DAC. Cellulosic ethanol from gasification technology is activated in all REF_FMx_CN scenarios, and the BECCS version of this technology provides cellulosic ethanol for GHG_FMx_CN scenarios. Cellulosic ethanol from fermentation technology with CCS also produces the required bioenergy for GHG_FMx scenarios till 2040. Different commercial and industrial wood and pellet boilers are activated for scenarios depending on available feedstock and defined constraints. Generally, boilers without CCS provide the required heat for reference scenarios, whereas boilers with CCS are utilized for GHG scenarios to meet the GHG reduction targets.

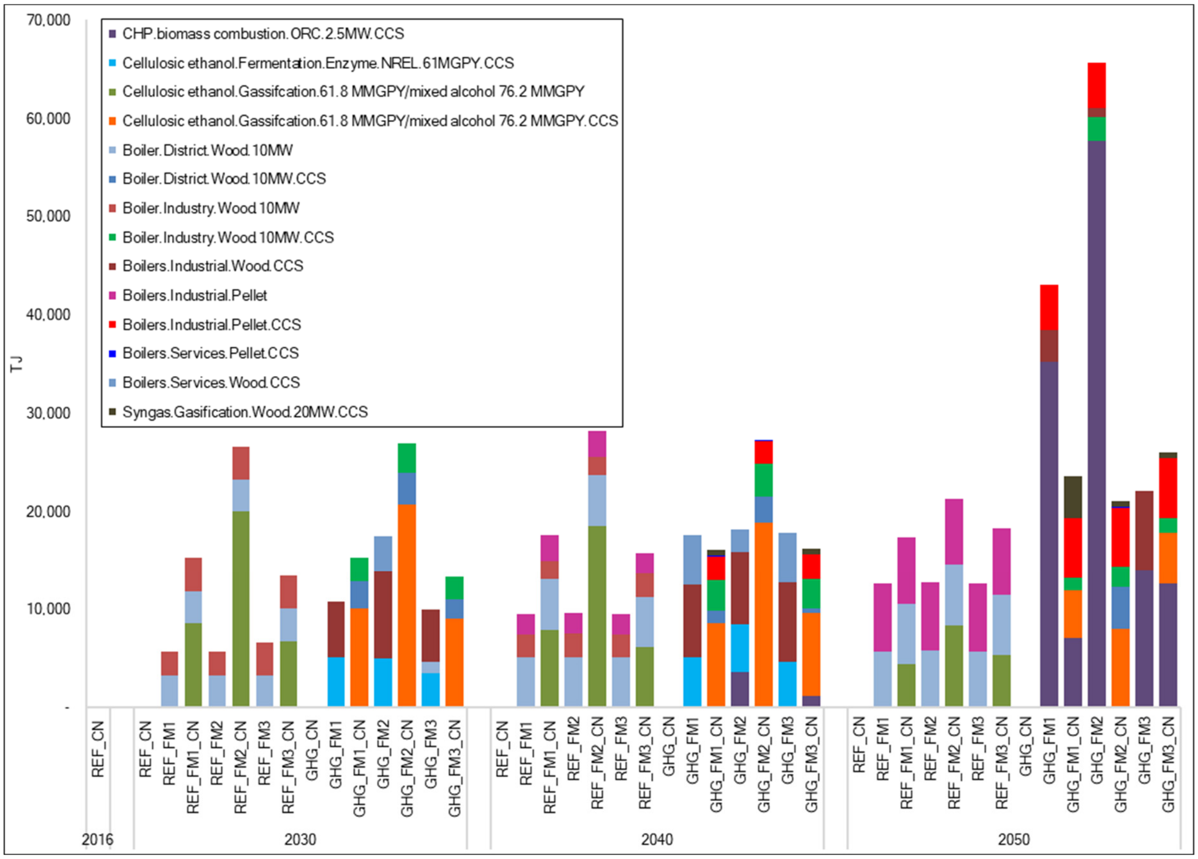


Figure A-II 7 BIOF technologies

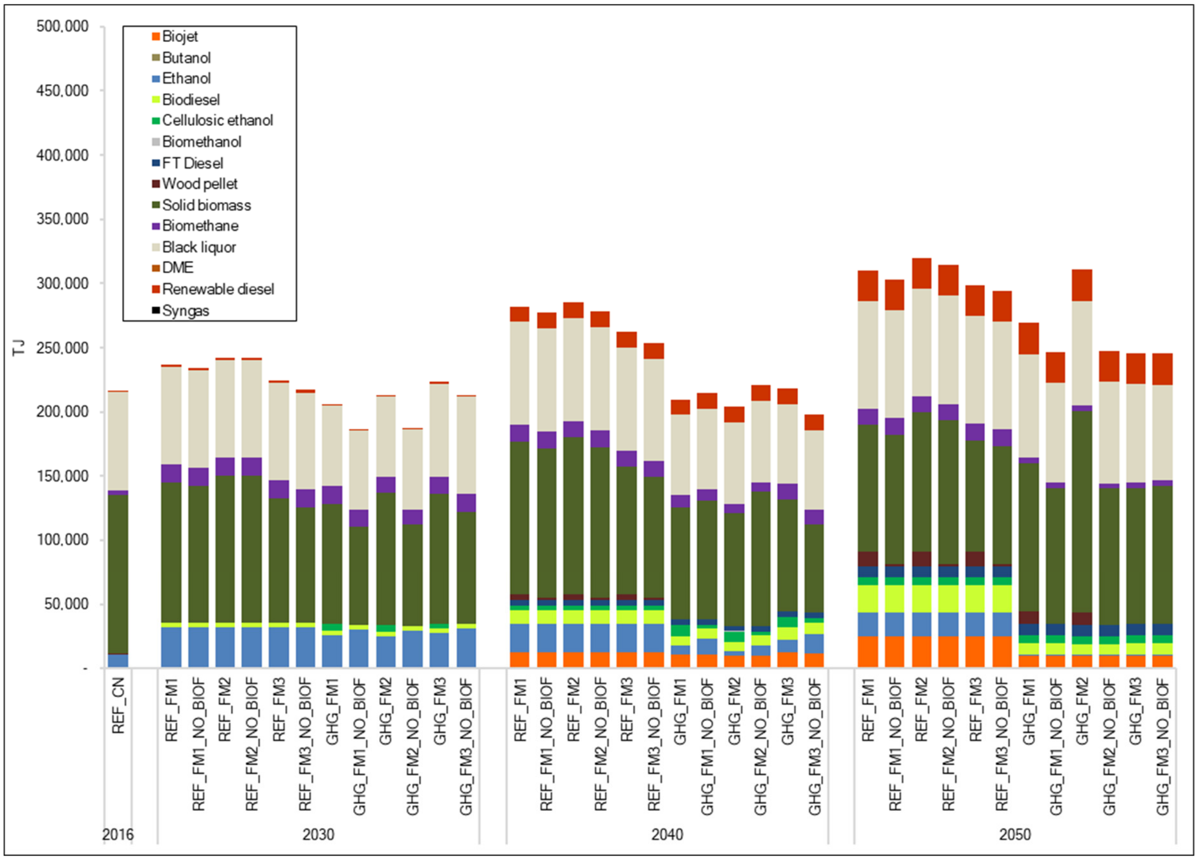


Figure A-II 8 The effect of BIOF on bioenergy consumption

APPENDIX III
SUPPORTING INFORMATION
THE ROLE OF HYDROGEN IN A NET-ZERO EMISSION ECONOMY UNDER ALTERNATIVE POLICY SCENARIOS

The following document provides supportive information for the CHAPTER 4 (Kouchaki-Penchah, Bahn, Bashiri, *et al.*, 2023).

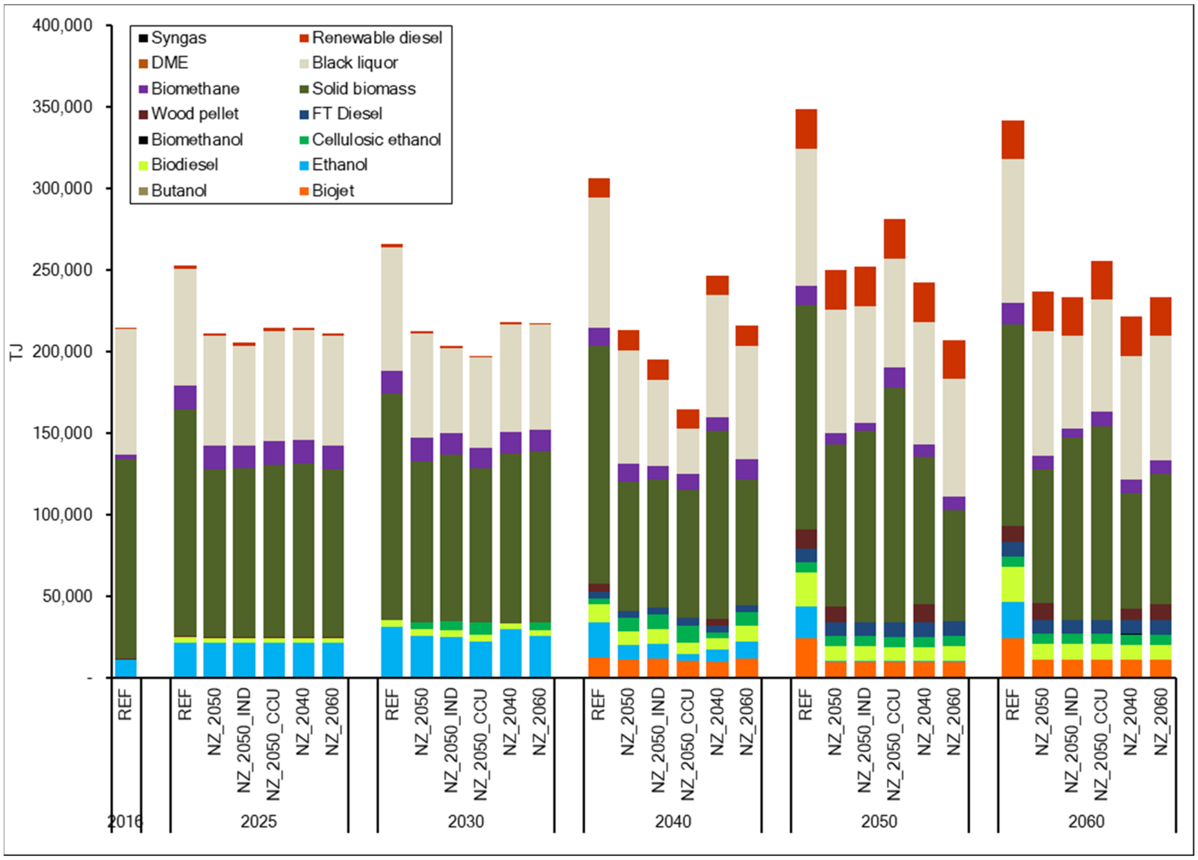


Figure A-III 1 Bioenergy consumption under different policy constraints

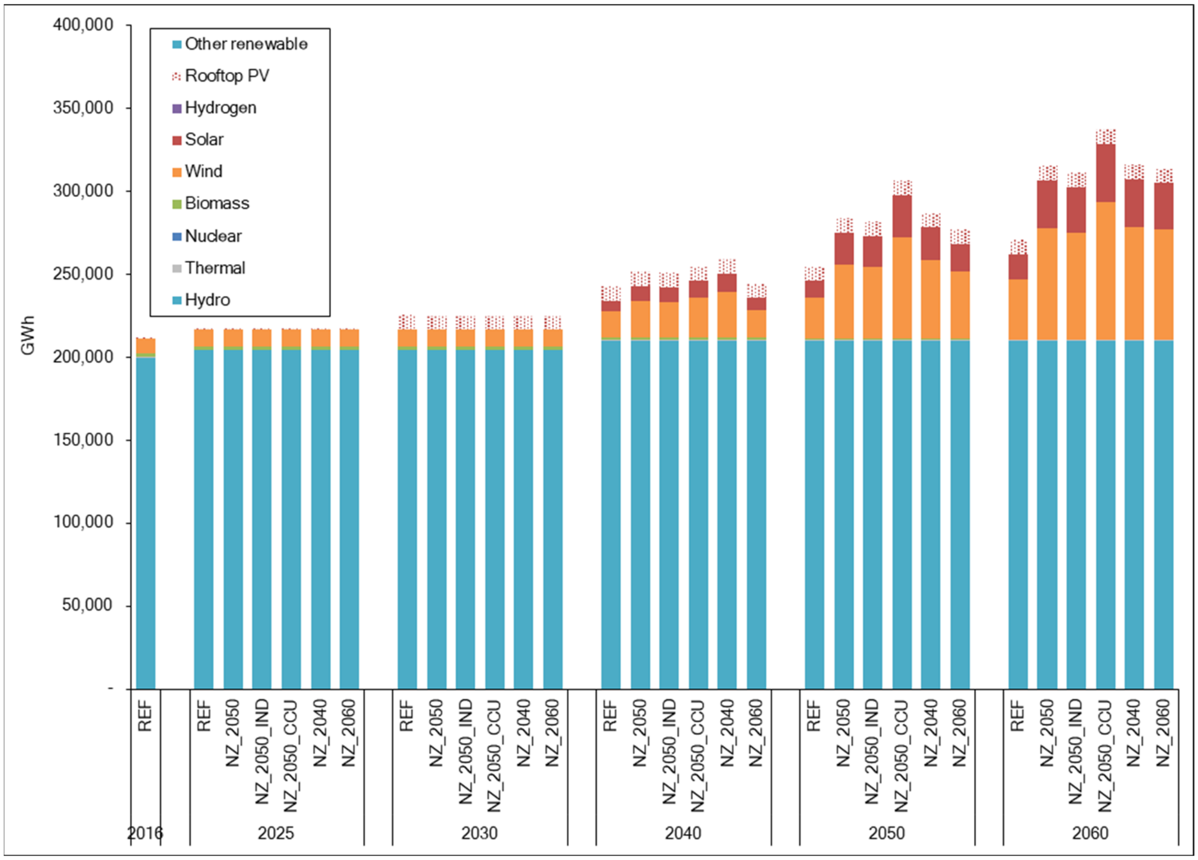


Figure A-III 2 Electricity production under different policy constraints

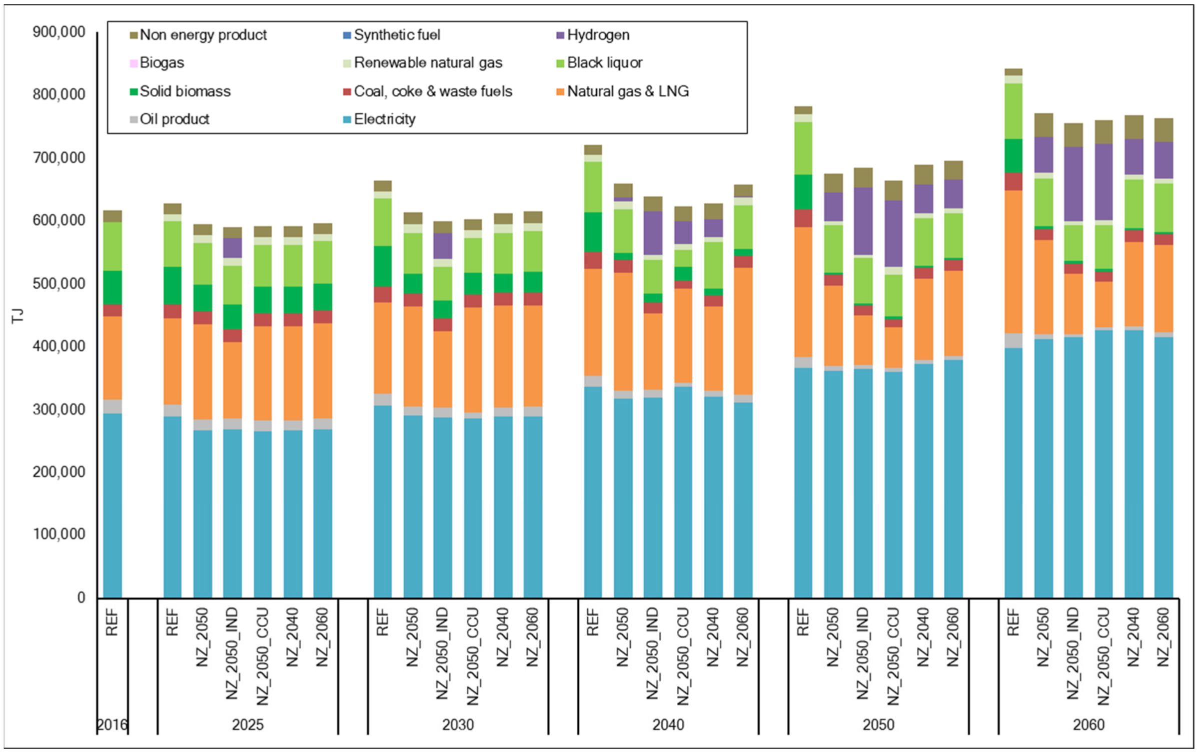


Figure A-III 3 Final energy consumption of industrial sector under alternative policy constraints

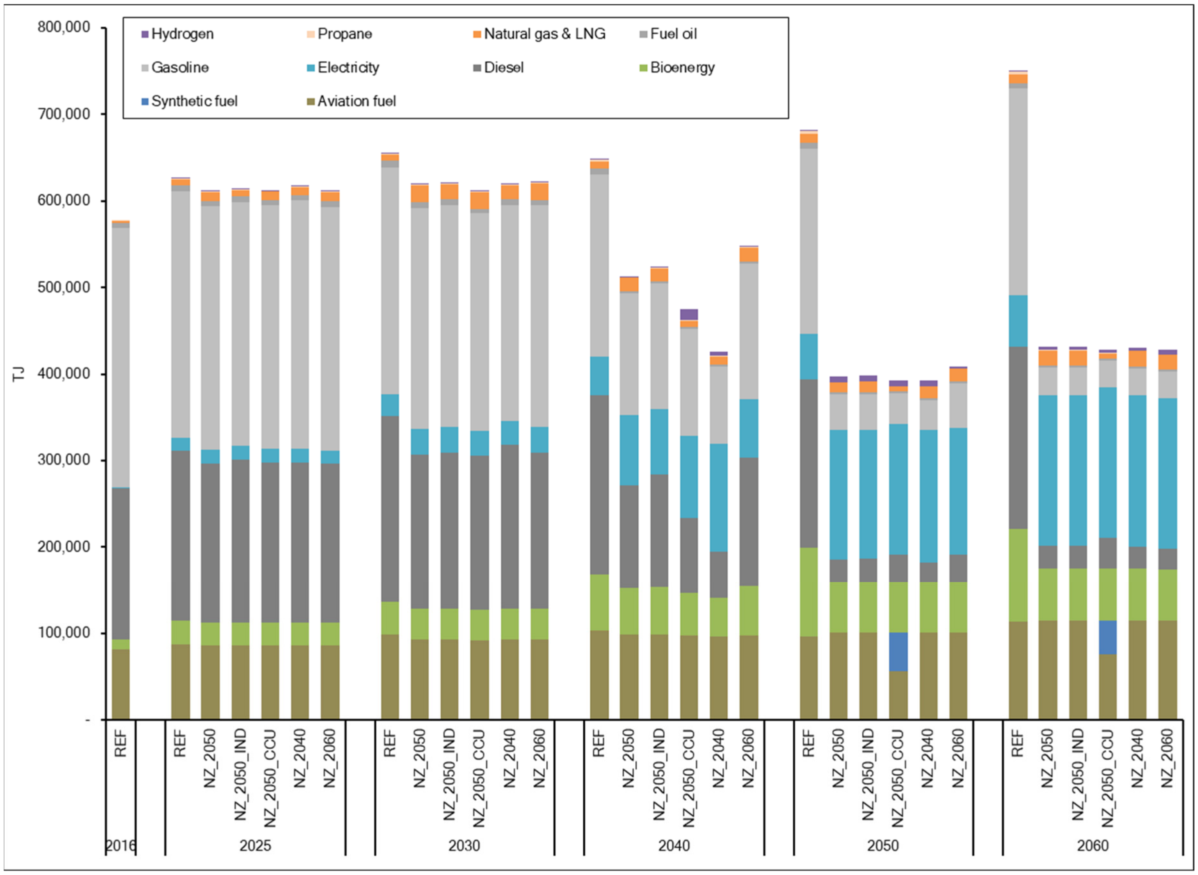


Figure A-III 4 Final energy consumption of transport sector under alternative policy constraints

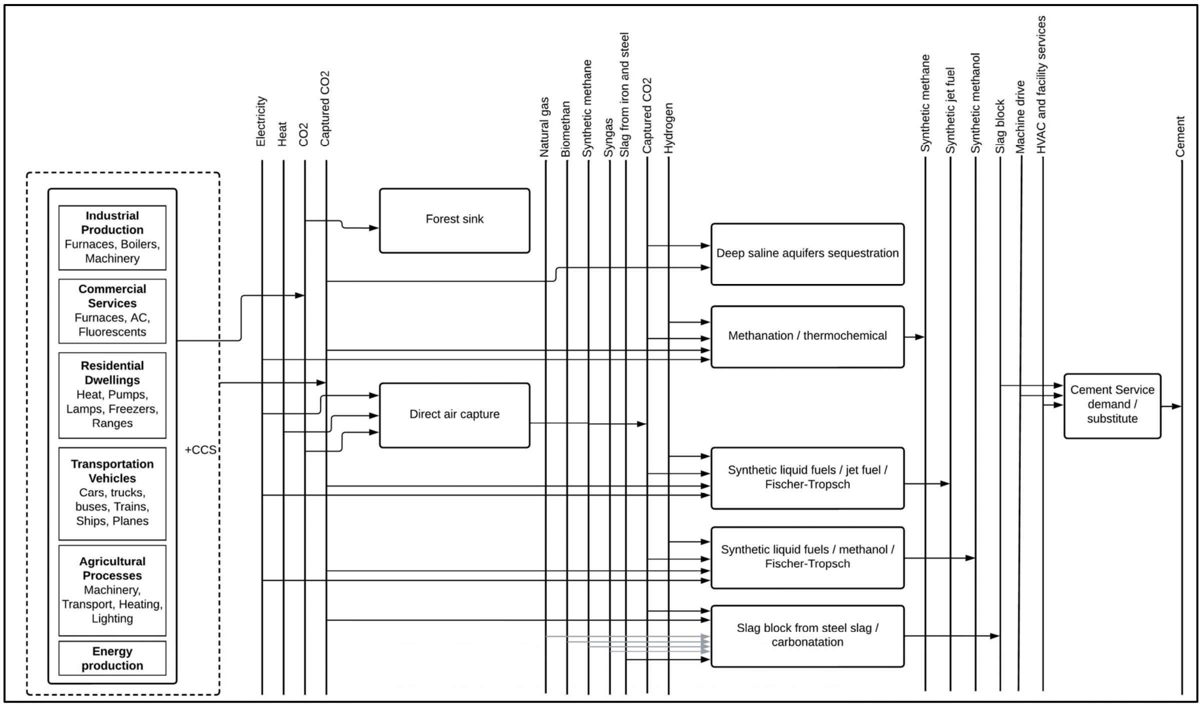


Figure A-III 5 Simplified reference energy system (RES) of carbon capture and usage (CCU) technologies and available sequestration in NATEM-Quebec

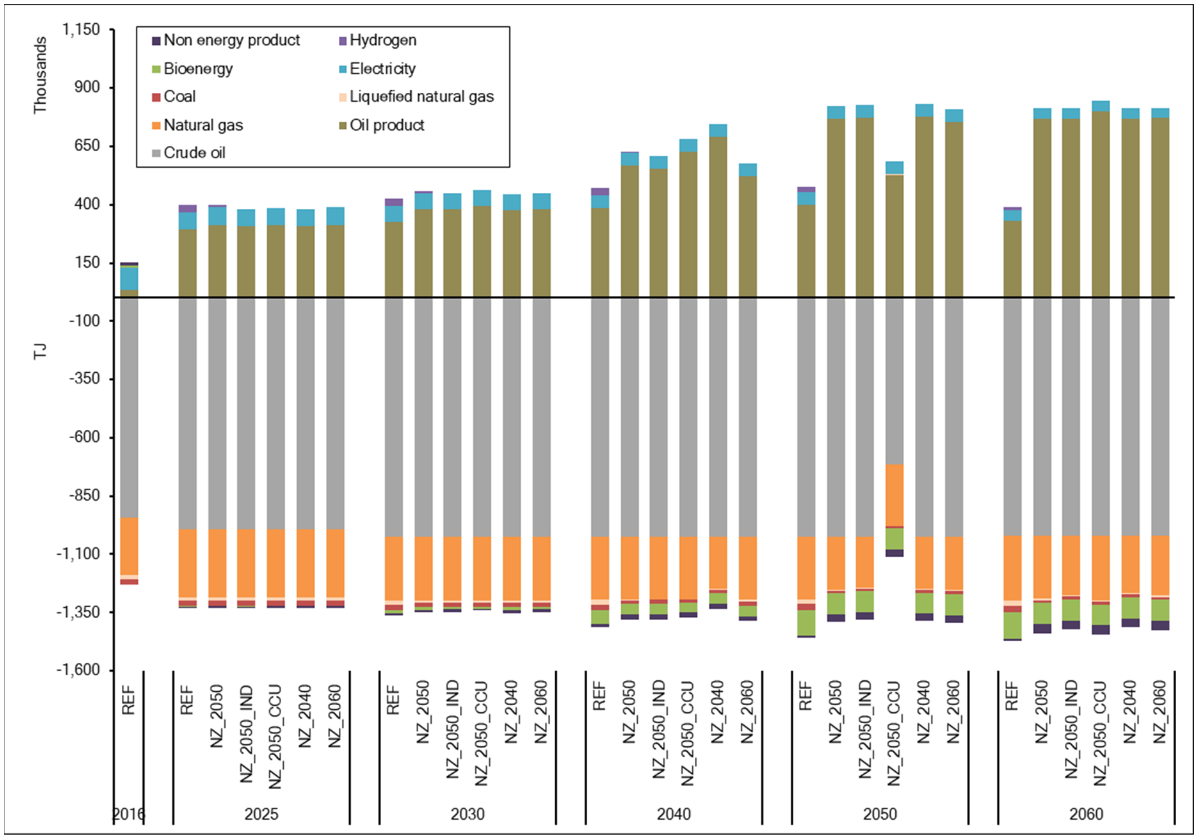


Figure A-III 6 Net export in Quebec under alternative policy scenario

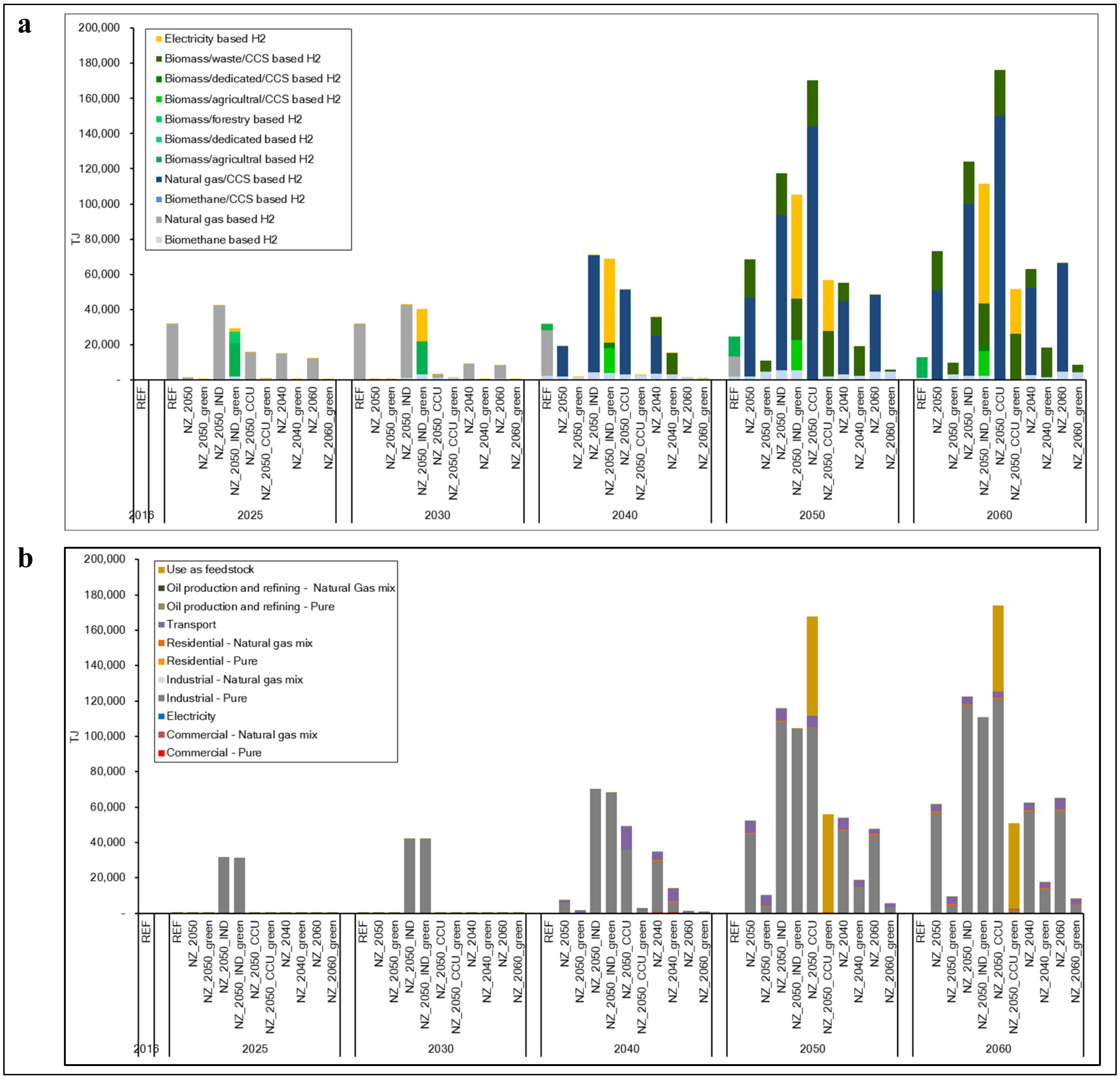


Figure A-III 7 (a) Hydrogen production and (b) hydrogen consumption profile under alternative policy scenarios

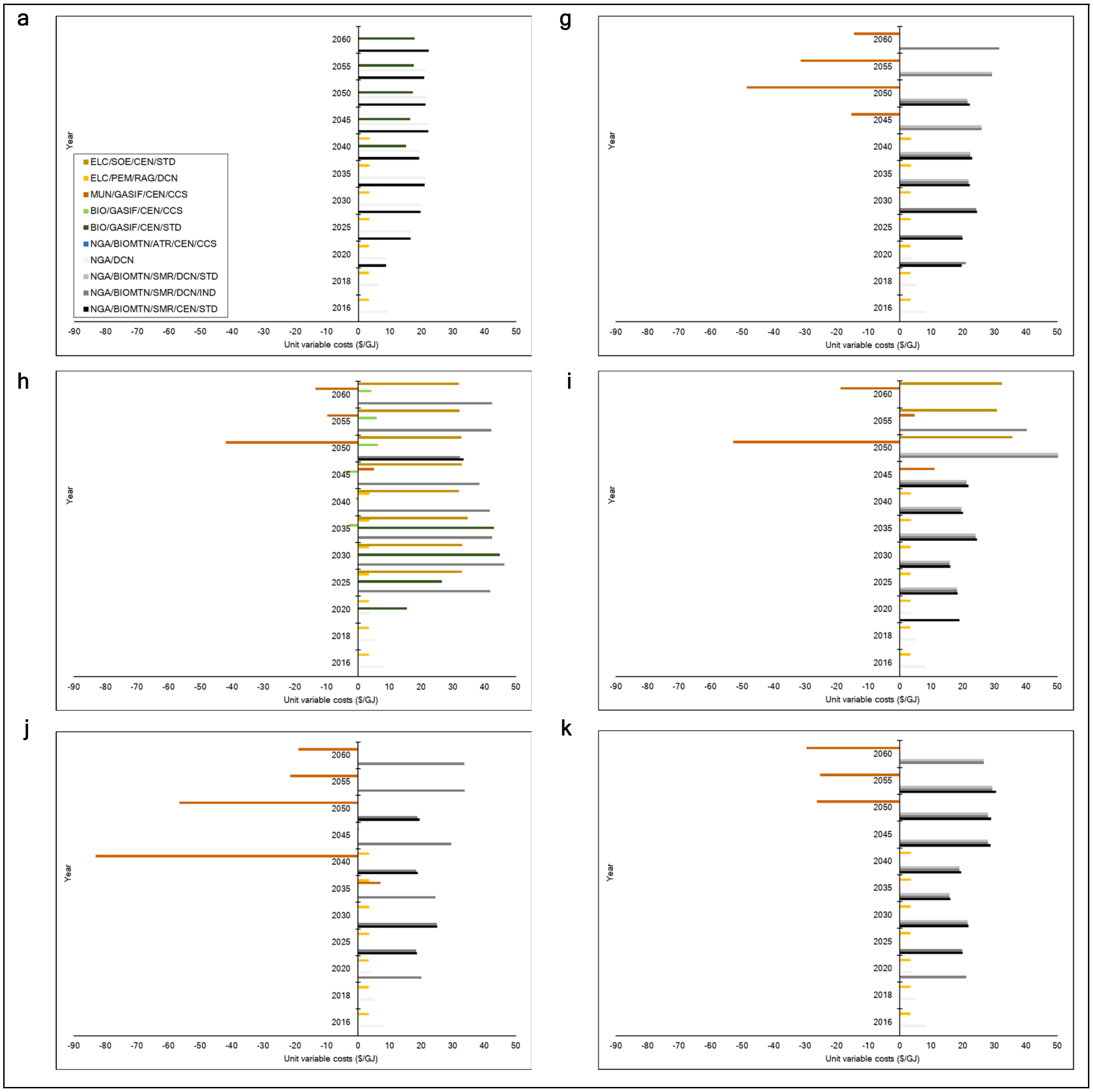


Figure A-III 8 Merit order of hydrogen technologies under a green hydrogen policy, (a) REF, (g) NZ_2050_green, (h) NZ_2050_IND_green, (i) NZ_2050_CCU_green, (j) NZ_2040_green, and (k) NZ_2060_green

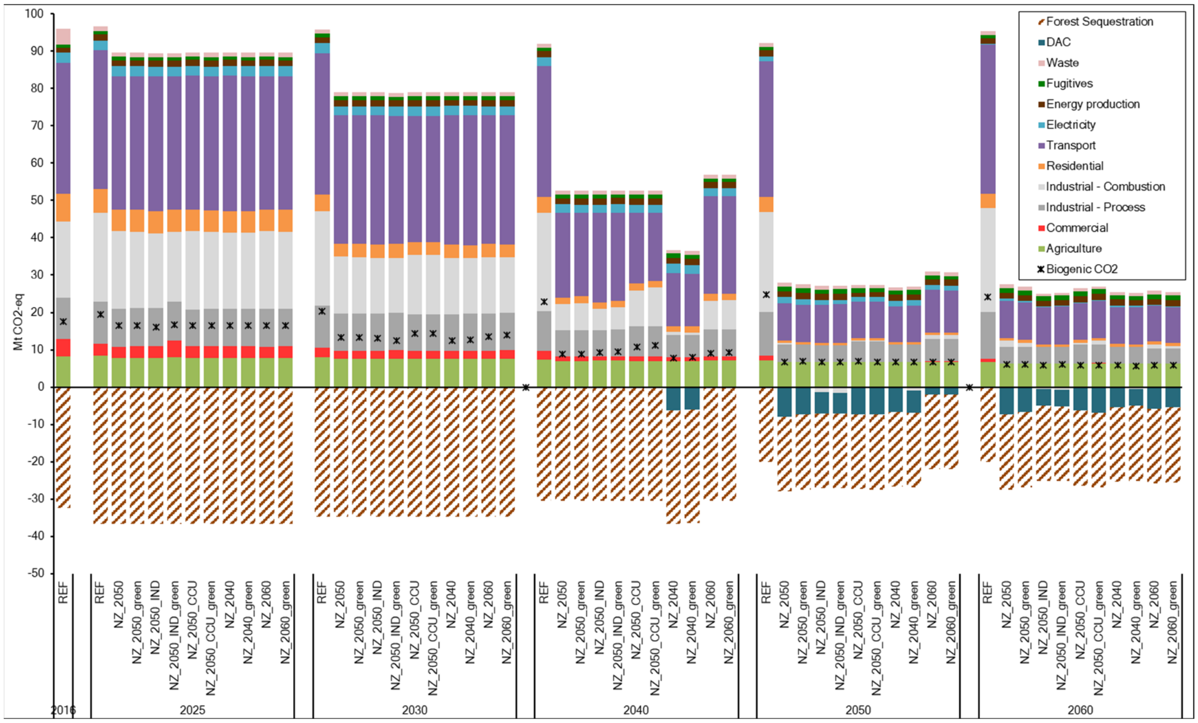


Figure A-III 9 GHG emissions by sector of all scenarios

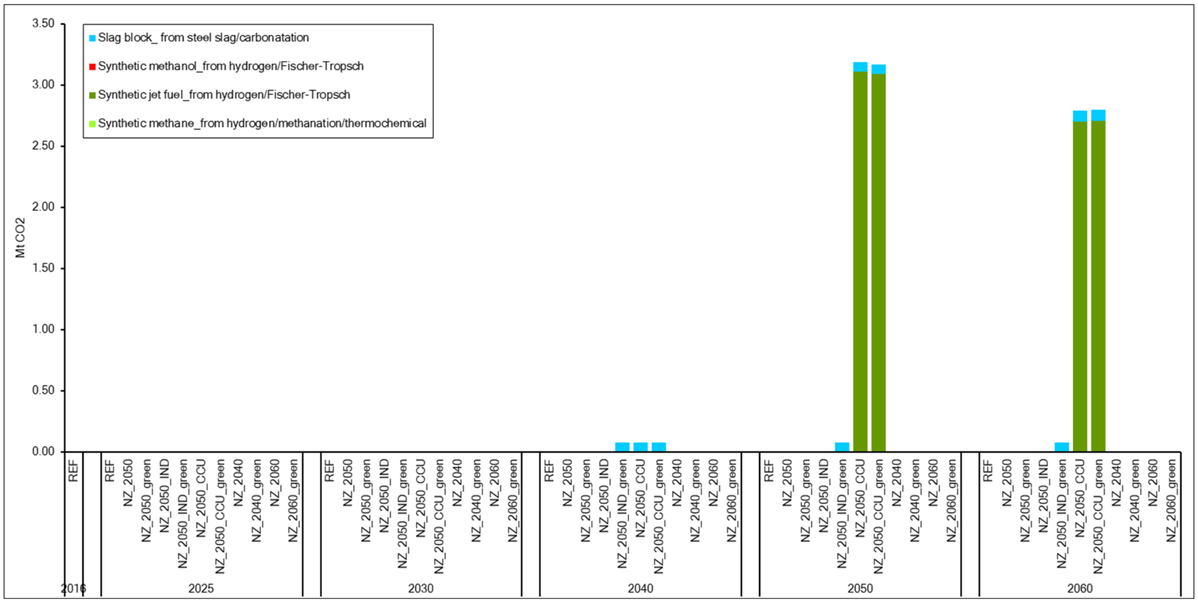


Figure A-III 10 Carbon capture and usage under alternative policy scenarios

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