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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

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 [1,2]. 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 [3], 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 [4]. These countries are looking for new opportunities to compensate for the declining demand for traditional forest products [1].

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 [5]. 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 [6]. 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 [7].

Many countries have announced ambitious plans to reduce their GHG emissions following national or international commitments such as the Paris Agreement [8]. For instance, Canada [9], the European Union [10], France, New Zealand, Spain, United Kingdom, are moving toward carbon neutrality by 2050, Sweden by 2045, Norway by 2030 [11], and China by 2060 [12]. In such a context, bioenergy can have a substantial role in fossil-free energy systems [13], 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 [14]. 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 [15].

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 [16]. 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 [6,16,17].

Many studies have already assessed the role of bioenergy for climate change mitigation following different approaches. Werner et al. [18] 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. [19] 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. [20] 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. [21] 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. [22] 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. [23] 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. [24] 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. [25], 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 [26], 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) [27] 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 [28, 29, 30, 31, 32], and [33]. It is also the case for models relying on the TIMES approach. For example, Hugues et al., [34] have used the TIMES-FR model to investigate the French bioenergy sector penetration under GHG emission constraints. Levasseur et al. [35] 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. [17] 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 et al. [36] 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 [37].

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 Methodological approach

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 [38].

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 [39]. TIMES complete documentation is publicly available [40], 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. . .) [26].

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. [26]. 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 [36]. 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 [41], 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 [42].

2.3 Forest-based biomass

2.3.1 Resource supply

Instead of a simple category labeled "forest residues" as the only forest-based feedstock in NATEM [36], 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 1. Forest-based feedstocks are characterized according to their physical properties, related activity, and final usage [6]. 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 [43–46].

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.

2.3.2 Bioenergies and conversion technologies

Figure 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

Table 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] [44,47]
[2] [43,44]
[3] [44,47,48]
[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

technologies to end-use technologies. Table 2 and Table 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 [49] 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 the Supplementary information (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 [50].

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 [50,51]. 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 [52]. Besides, charcoal production and roasting [51] are also considered as thermochemical conversion technologies that produce charcoal, briquette, and roasted wood. Biochemical processes include fermentation and anaerobic digestion [52]. Different types of fermentation conversion processes have been investigated in this study. Hybrid conversion processes integrate thermochemical and biochemical conversion processes [7]. A description of biofuel conversion pathways is available in the Supplementary information (Part B).

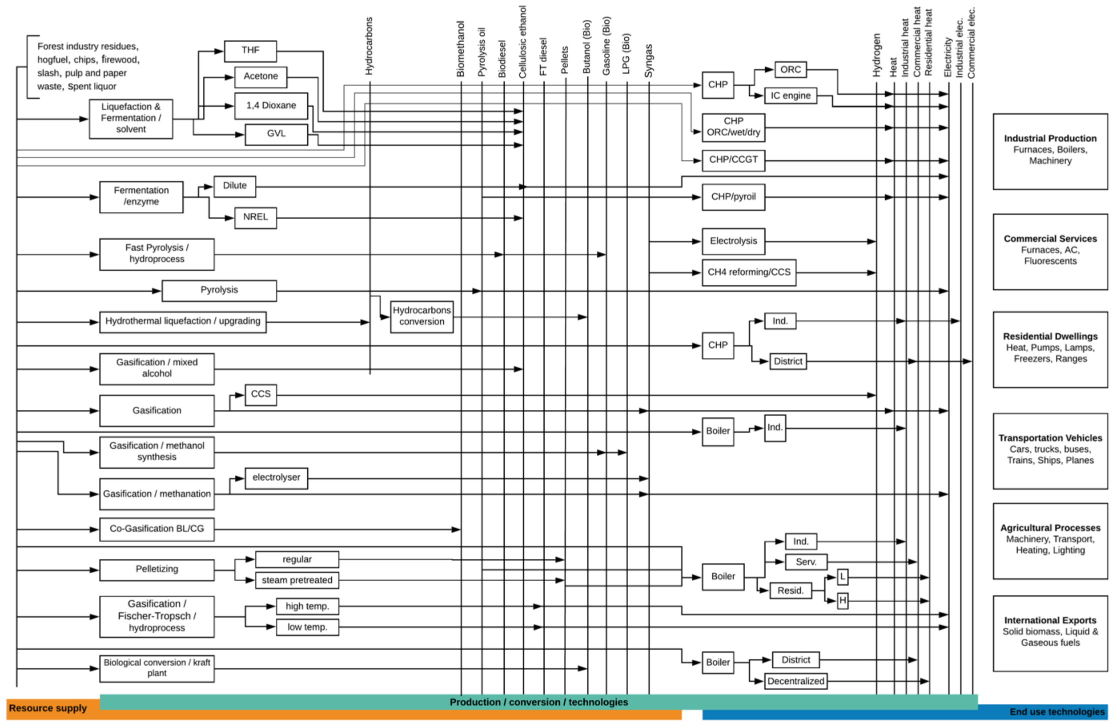

Figure 1: Detailed forest-based bioenergy conversion processes in NATEM-Quebec.

2.4 Energy and emission scenarios

Four scenarios (Table 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 [70]. And again, all these scenarios consider existing governmental energy and climate policies [71–74].

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).

3 Result analysis

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). 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.

Table 2: Primary conversion processes.

Technology	Conversion process	Bioenergy	Reference
Biomass HTL. Upgrading system 69.9 MGGEPY	Hydrothermal liquefaction	Hydrocarbons	[53]
Co-Gasification. Methanol grade AA. Black liquor. Crude glycerol	Co-Gasification	Biomethanol	[54]
Fast pyrolysis and hydroprocessing 35 MGPY	Fast pyrolysis	Gasoline(bio), Biodiesel	[55,56]
Fermentation. Butanol Production	Fermentation	Butanol(bio), Heat	[35]
Fermentation. Ethanol. Enzyme. Dilute-acid 53.4MGPY	Fermentation	Cellulosic bioethanol, Electricity	[57,58]
Fermentation. Ethanol. Enzyme. NREL 61MGPY	Fermentation	Cellulosic bioethanol	[57,59]
Fischer-Tropsch. Catalytic. Hydroprocessing. High temperature. Flow gasifier 41.7MGPY	Gasification/ Fischer-Tropsch	FT diesel, Electricity	[60]
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	[31]
Gasification facility. Gasifier + methanation. Wood. Electrolyser	Gasification/ methanation	Syngas	
Gasification.Wood.20MW	Gasification	Syngas, Electricity, Heat	[61]
Gasification to ethanol 61.8 MMGPY/mixed alcohol 76.2 MMGPY	Gasification/mixed alcohol	Cellulosic bioethanol	[56,62]
Gasification. Bio. CCS. Hydrogen	Gasification/ Hydrogen	Hydrogen	[61,63]
Gasification. Methanol synthesis, Methanol to Gasoline (MTG) 49.6 MGPY	Gasification/ methanol synthesis	Gasoline(bio), LPG (bio)	[64]
Liquefaction. Fermentation. Ethanol. Solvent. 1,4-Dioxane 39.4MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	[57]
Liquefaction. Fermentation. Ethanol. Solvent. Acetone 34.8MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	
Liquefaction. Fermentation. Ethanol. Solvent. GVL 50.6MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	[57,65]
Liquefaction. Fermentation. Ethanol. Solvent. THF 53.3MGPY	Liquefaction & Fermentation	Cellulosic bioethanol	[57]
Pellet. Production. Forest residue. Regular 190kt	Pelletizing	Pellets	[66]
Pellet. Production. Forest residue. Steam pretreated 290kt	Pelletizing	Pellets	
Pyrolysis. Wood 10MW	Pyrolysis	Pyrolysis oil	[61]
CHP ORC system. Wet/dry wood 2.08MWe	CHP/ORC/Wet/dry	Electricity, Heat	[67]
CHP. biomass combustion. ORC 2.5MW	CHP/ORC	Electricity, Heat	[68]
CHP. biomass gasification. IC engine 3MW	CHP/Gasification/ IC engine	Electricity, Heat	
CHP. District. Wood 20MWth	CHP/District	Heat, Electricity	[61]
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	[31]
Boilers. Residential. Wood. High	Boilers/Residential	Heat	
Boilers. Residential. Wood. Low	Boilers/Residential	Heat	
Boilers. Services. Wood	Boilers/Services	Heat	

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 3 displays energy-related GHG emissions by sector (agriculture, commercial, electricity, industrial, residential, production, and transportation). Transportation is responsible for more than

Table 3: Secondary conversion processes.

Technology	Conversion process	Bioenergy	Reference
CH4 reforming. CCS. Hydrogen	CH4 reforming/Hydrogen	Hydrogen	[61,63]
Electrolysis. Hydrogen	Electrolysis/Hydrogen	Hydrogen	[61,69]
CHP. Combined-Cycle Gas Turbine CCGT. SNG 34-55MWe	CHP/CCGT	Electricity, Heat	[67]
CHP. Oil/Bio-Oil 0.2-2MWe	CHP/Bio-Oil	Electricity, Heat	
Boilers. Industrial. Oil	Boilers/Industrial	Heat	[31]
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	

Table 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

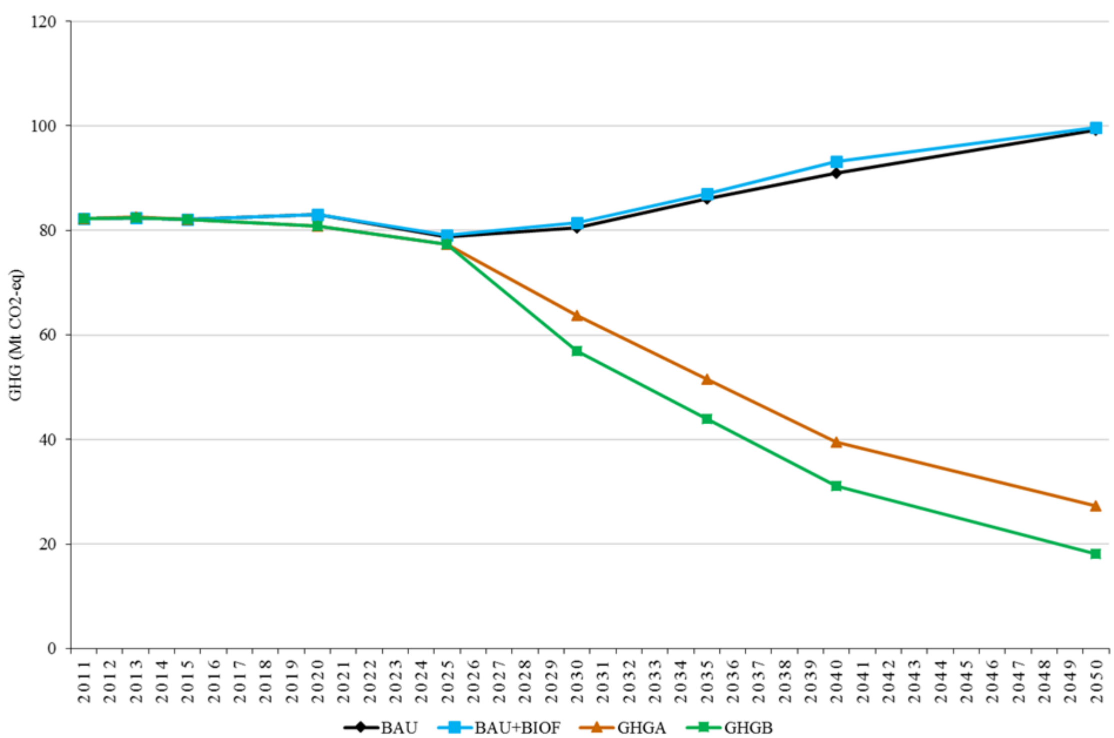

Figure 2: Total GHG emissions in Quebec.

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.

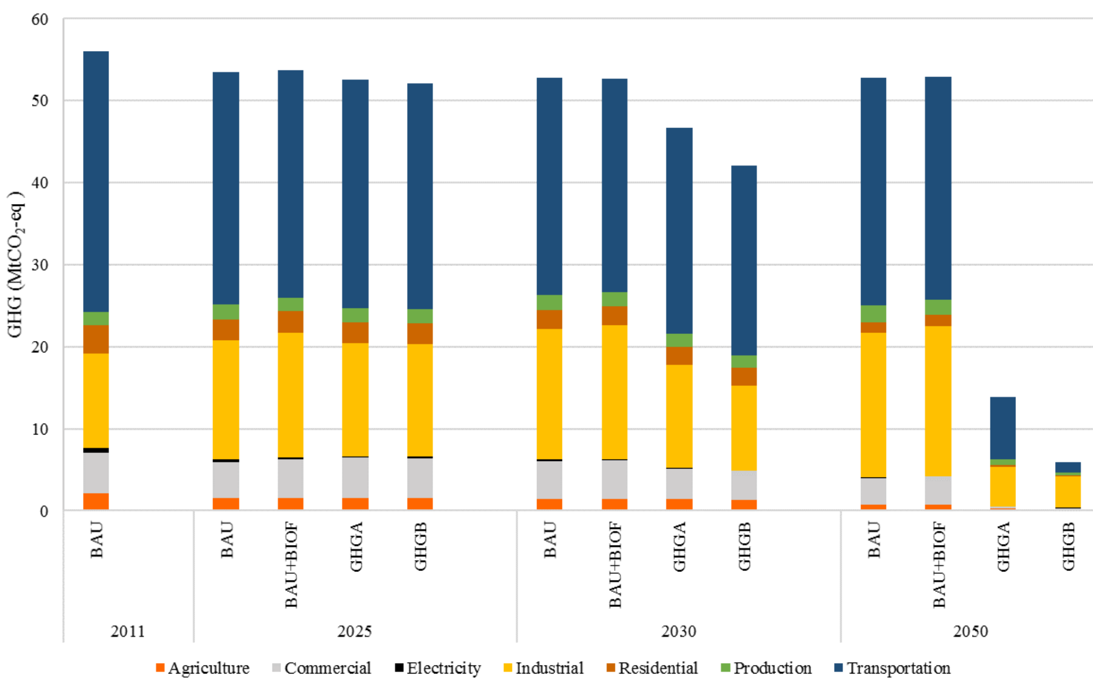

Figure 3: Energy-related GHG emissions by sector in Quebec.

3.2 Primary energy production

Primary energy production (PEP) highly relies on hydroelectricity and biomass in Quebec (Figure 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.

3.3 Forest-based residues as feedstock

Figure 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

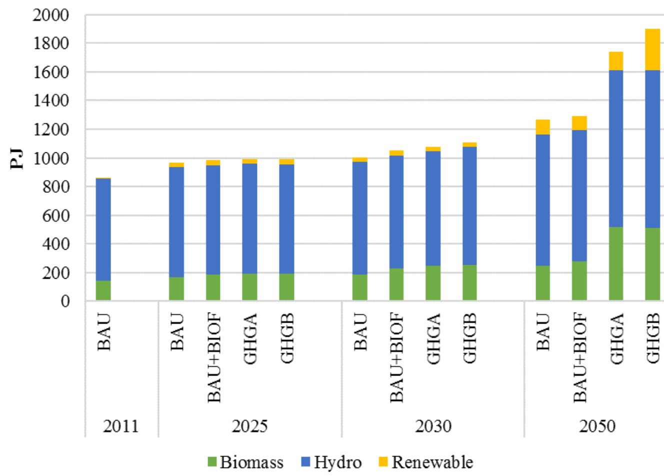

Figure 4: Primary energy production in Quebec.

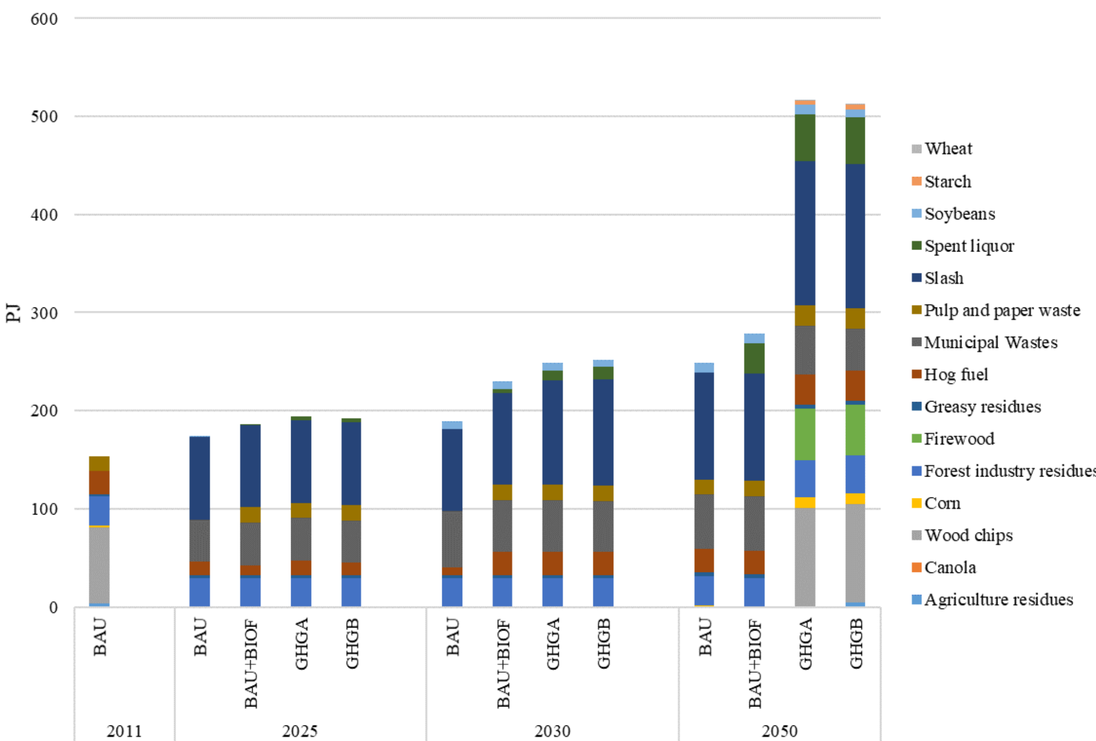

Figure 5: Consumption of feedstock by type for bioenergy production in Quebec.

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.

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 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.

3.4 Final energy consumption

Figure 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).

3.5 The contribution of bioenergy in final energy consumption

Bioenergy use increases over the time horizon in BAU and BAU+BIOF scenarios (Figure 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

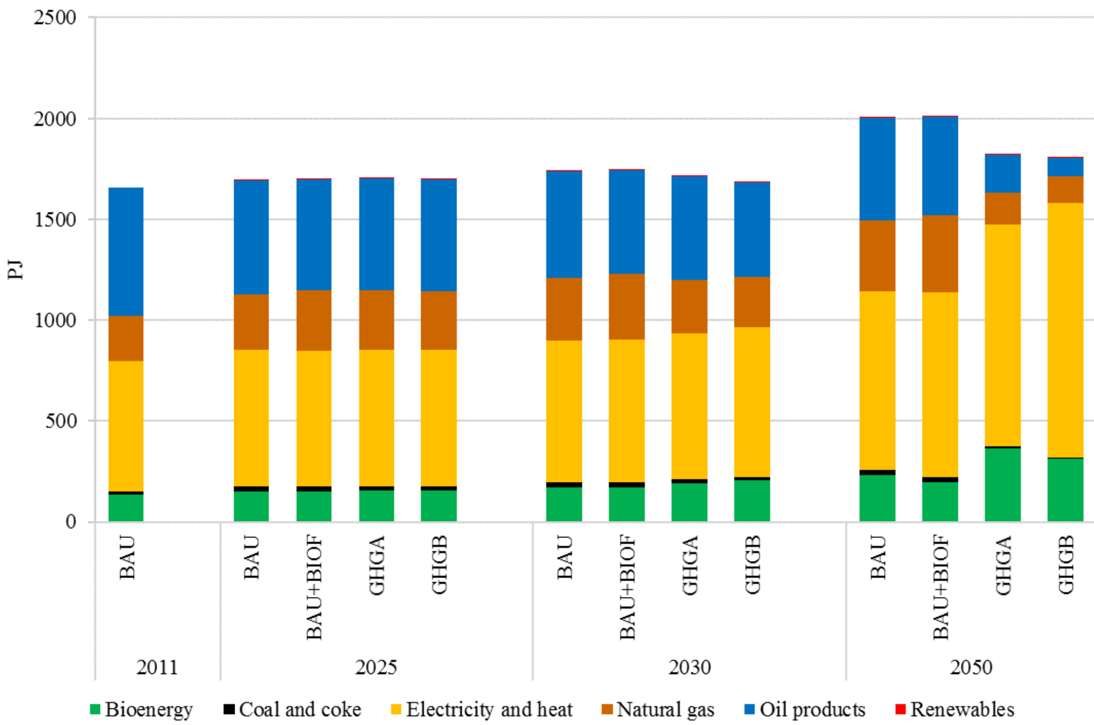

Figure 6: Final energy consumption in Quebec.

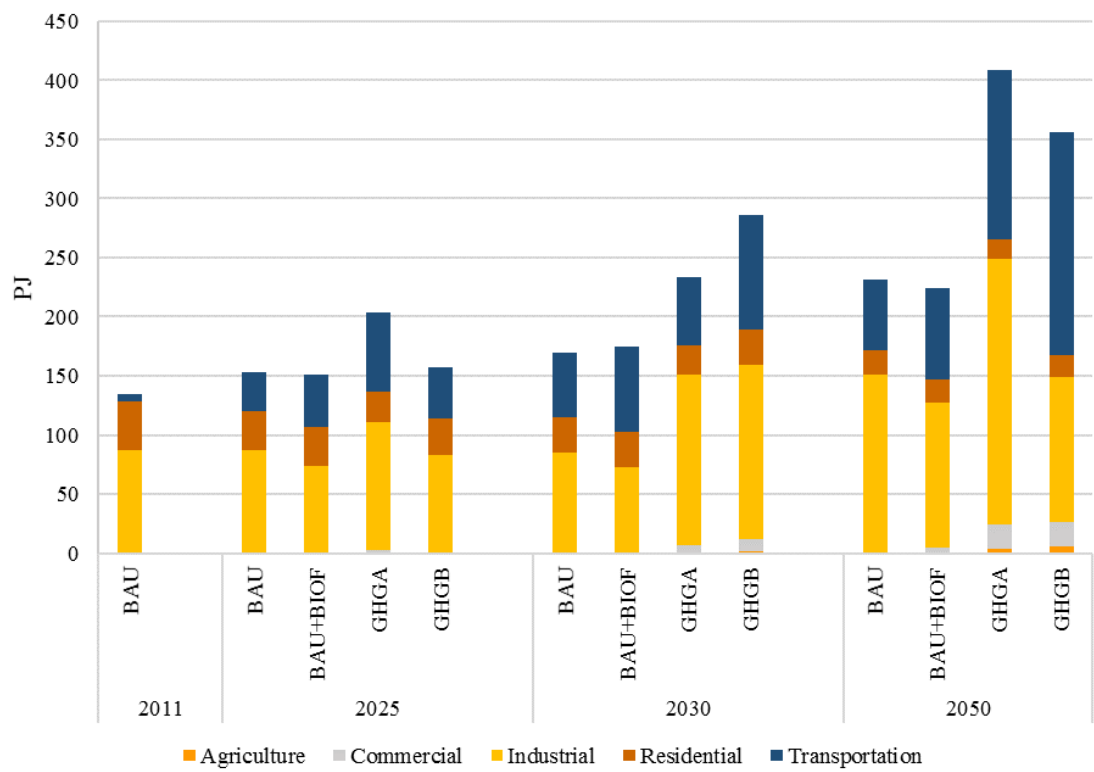

Figure 7: Consumption of bioenergy by end-use sector in Quebec.

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 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.

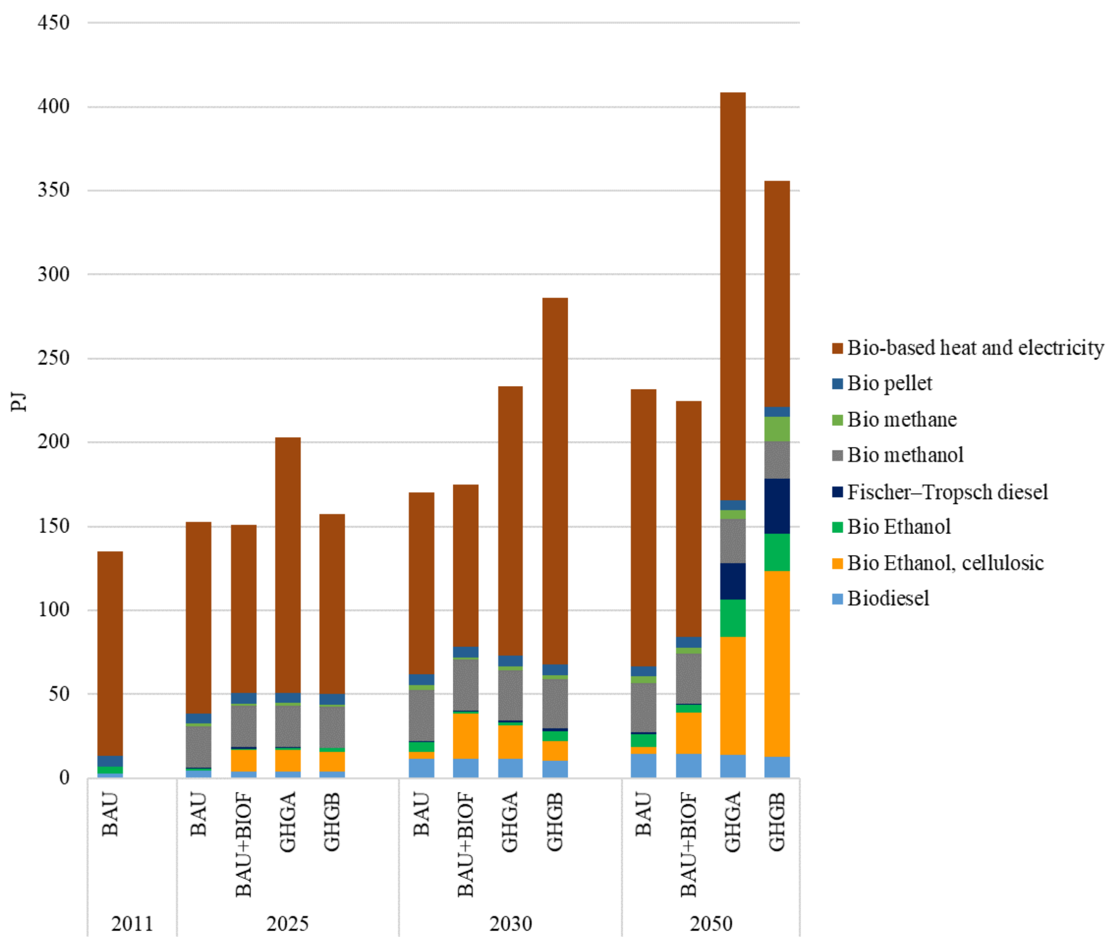

Figure 8: Consumption of bioenergy by type in Quebec.

Bioenergy production from forest-based technologies is displayed in Figure 9. Besides, biomass consumption by these technologies is given in Table 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.

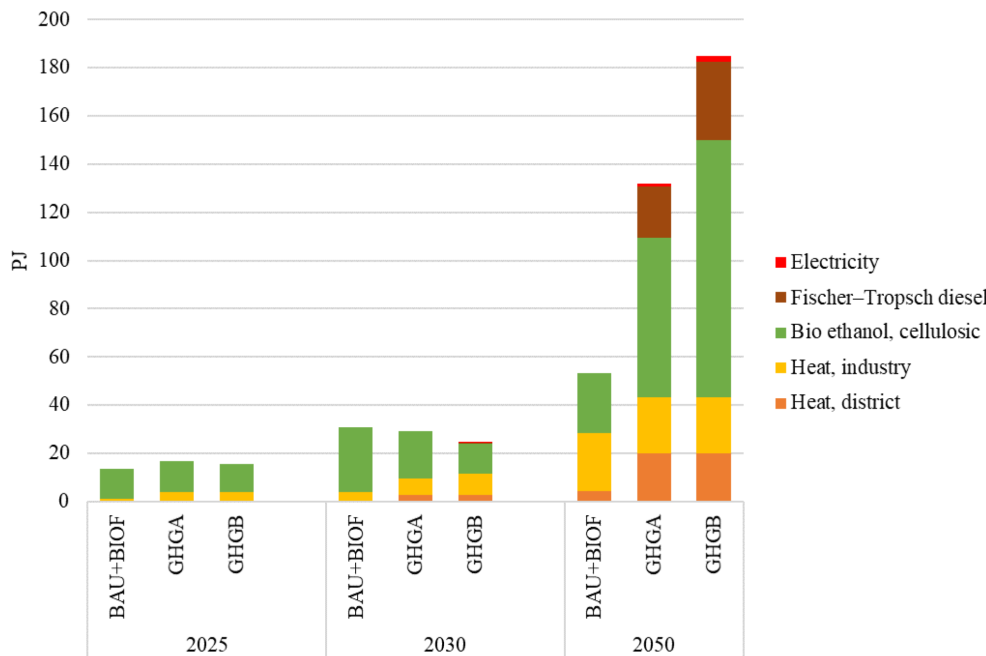

Figure 9: Bioenergy production from forest-based technologies in Quebec.

Forest slash and spent liquor are the primary feedstock to produce bioenergy from forest-based technologies (Table 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 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. [57], 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 consumptions.

3.6 Mitigation costs

Figure 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).

Table 5: Forest-based biomass consumption by specific technologies.

Technology	Scenario / Feedstock/Year	2025 BAU+BIOF	2025 GHGA	2025 GHGB	2030 BAU+BIOF	2030 GHGA	2030 GHGB	2050 BAU+BIOF	2050 GHGA	2050 GHGB	Bioenergy
Boiler. district. wood. 10MW	Spent liquor	0.01	0.01	0.01	0.01	3.36	3.36	5.10	23.00	23.14	Heat, district
Boiler. industry. wood. 10MW	Spent liquor	1.07	4.06	4.07	4.40	7.34	9.52	25.85	25.23	25.09	Heat, industry
Gasification to ethanol 61.8 MMGPY/ mixed alcohol 76.2 MMGPY	Chips								100.11	35.01	Cellulosic bio-ethanol
	Forest industry residues					29.29				38.07	
	Hog fuel						23.45			30.48	
	Slash	26.80	27.39	25.18	56.68	11.88	2.16	52.59	39.68	121.69	
Fischer-Tropsch. catalytic. hydro-processing. high temperature. flow gasifier.41.7 MGPY	Chips									65.10	FT diesel, electricity
	Slash						1.21		42.36		

[a, b] [61]
[c] [56,62]
[d] [60]

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) [38]. 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.

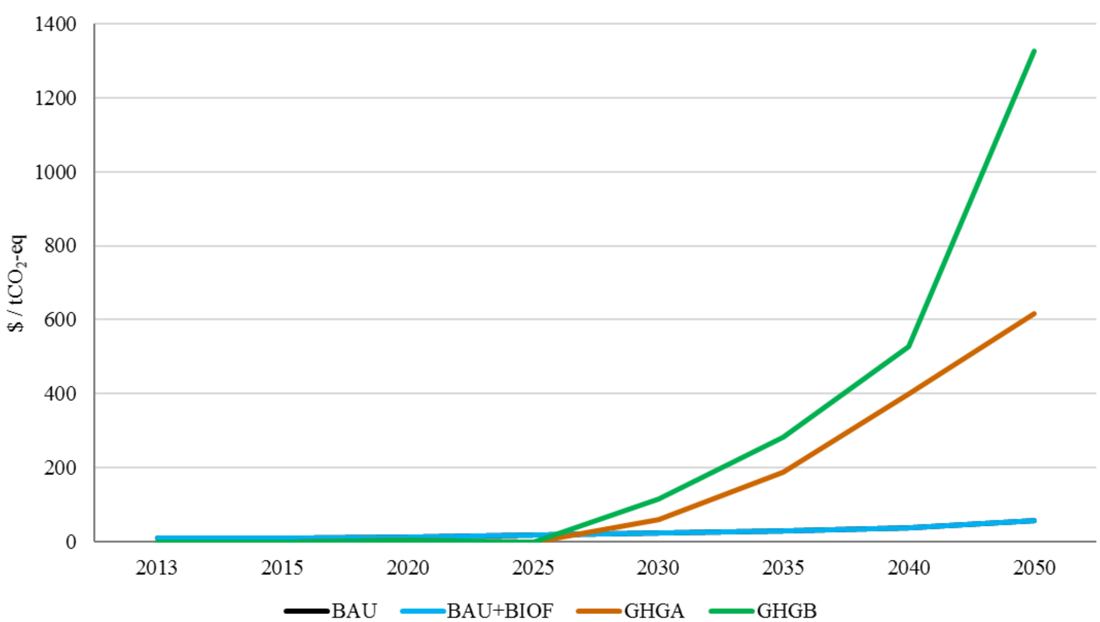

Figure 10: Marginal abatement cost for one ton of CO_2-eq in Quebec.

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 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.

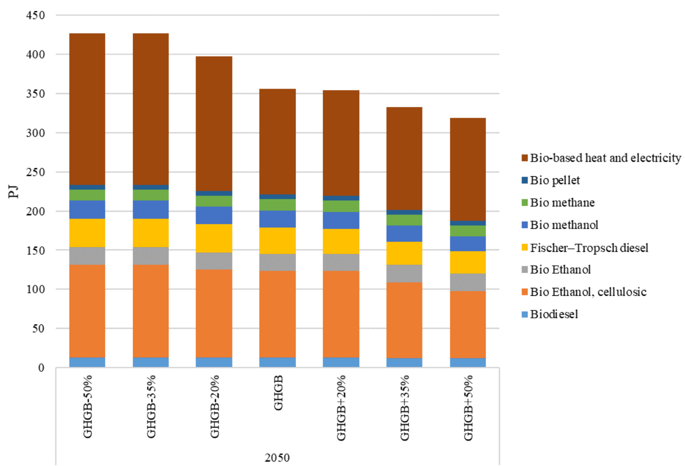

Figure 11: Bioenergy production at different prices of feedstock in GHGB scenario in 2050 in Quebec.

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 [43], 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 [6]. 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 [20]. Also, surplus forest growth (low-quality roundwood) is achievable as a potential source of feedstock, which can, in turn, strengthen the forest value chain [75].

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 [16]. 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. [59] and Wright and Brown [53] 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 [60] 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 [61] 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 [26,36,76]. 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 [1,2,5–7,37]. 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 1 in any of the 70 countries using a TIMES approach [36]. As a reminder, detailed techno-economic data is given in the Supplementary information (Part A).

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 [15]. 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.

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