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Sustainability Impact Assessment of Forest Bioenergy Value Chains in Quebec (Canada)—A ToSIA Approach

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Abstract: Forest bioenergy value chains can offer attractive opportunities to promote economic development and mitigate climate change. However, implementing profitable and efficient forest biomass value chains requires overcoming barriers that continue to hinder the development of bioenergy systems in several jurisdictions. The objective of this study was to compare the economic, social, and environmental sustainability of various potential configurations of forest bioenergy value chains, including forest biomass supply and bioenergy production chains, in the Capitale-Nationale region of Quebec (Canada), which is a jurisdiction that has considerable forest resources but makes little use of bioenergy. We based our study on the ToSIA model parameterization and compared various policy measures, biomass supply, and logistics scenarios for 2008 and 2030. Our results showed that wood chip and pellet value chains in the Capitale-Nationale region would positively contribute to the regional economy in 2030, even in the absence of subsidies. Moreover, actions to increase biomass feedstock mobilization in 2030 would lead to an increase in gross value added, employment, and energy production in the region compared with 2008 and a greater increase than other considered policy or logistical measures. However, increased biomass feedstock mobilization would also mean higher relative GHG emissions and more fossil fuel energy input per unit of bioenergy than in the other scenarios. Conversely, optimizing biomass feedstock and combustion technologies could help minimize the fossil fuel energy input needed and GHG and some non-GHG pollutant emissions. Overall, our study suggested that implementing policy and logistical measures for forest biomass value chains could make the significant mobilization of forest bioenergy attainable and, in turn, Quebec's 2030 bioenergy target of 17 petajoules realistic.

Keywords: forest bioenergy; value chain; sustainability; chip; pellet; environmental; economic; social

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1. Introduction

The contribution that the forestry sector can make to mitigating greenhouse gas (GHG) emissions has started to be recognized in recent decades [1,2]. The forestry sector's GHG mitigation potential is notably associated with the replacement of fossil-based GHG-intensive energy sources and materials with forest biomass-based equivalents. In that context, bioenergy from forest biomass is gaining more and more ground as a renewable energy sources [3], particularly in countries with large forested areas such as Canada, the United States, Sweden, and Finland. Sources of forest biomass usually include: (i) byproducts of forest management such as tree branches, tree tops, and low-quality logs; (ii) byproducts of wood processing such as wood chips, wood shavings, and sawdust; and (iii) post-consumer wood products such as wood from deconstruction [4]. Several policies and strategies have been developed to facilitate forest bioenergy's market penetration [5], particularly for heating and cogeneration (the combined production of heat and electricity) [6].

Community-based forest bioenergy systems have been found to provide rural development benefits [7] and employment opportunities [8–11]. However, implementing profitable and efficient forest biomass supply chains requires overcoming specific technical and financial barriers that continue to hinder the development of bioenergy systems in several jurisdictions [12–15], particularly areas with overall low energy prices. In addition, procuring primary biomass for bioenergy (along with wood for sawn wood and pulp, among other products) from forests raises concerns about potential ecological impacts on ecosystem functioning and biodiversity [16]. Concerns about air pollution and its associated health issues caused by biomass combustion are also worthy of consideration [17–19].

Communities and decision-makers envisioning forest bioenergy projects, therefore, need to assess, quantify, and compare several sustainability-related economic, social, and environmental aspects related to their project [20–22]. For example, the Quebec government has set a goal to increase forest biomass-based bioenergy production in the province by 50% compared to 2013 and to 25% of total renewable energy production by 2030 [23]. However, despite its abundant forest resources and mature, highly developed wood product industry, Quebec's bioenergy sector is still in its infancy. The province has ample local sources of renewable energy (the main one being hydraulic power) that represented about 46% of its total energy production in 2018: hydraulic power accounted for 33% of its energy balance sheet in 2018, while biomass represented only 7% [24]. At the provincial level, biomass feedstock is mainly mobilized in the form of wood processing residues used for internal heat and electricity production in the wood product sector. This accounts for about 66% of total provincial forest biomass consumption, while the remaining approximate 34% is consumed in the residential sector, mainly as firewood [24]. Primary data on the potential impacts and outcomes of forest bioenergy systems in the province are therefore still scarce, and this is holding back the emergence of forest bioenergy projects despite the presence of a political will.

The aim of the study was to explore how decisions at the policy and logistical levels influence the sustainability of forest bioenergy. The objective of this study was to compare the economic, social, and environmental impacts of various potential configurations of forest bioenergy value chains, including forest biomass supply and bioenergy production chains, in the Capitale-Nationale region of Quebec (Canada). A variety of forest bioenergy value chains—including different wood harvesting methods, biomass feedstock (wood chips and wood pellets), levels of biomass mobilization, combustion technologies and policy measures—were investigated. The province of Quebec was selected as a case study as it is a jurisdiction with a large forest industrial sector, little existing forest bioenergy capacity but expectations to use it in the future. We based our study on parameterization of the Tool for Sustainability Impact Assessment (ToSIA). We hypothesized that increasing the biomass supply and optimizing the match between biomass feedstock and combustion technologies would create large environmental, social, and economic benefits.

2. Materials and Methods

2.1. Study Area

The province of Quebec is in Eastern Canada, bordered by the United States to the south and intersected by the St. Lawrence River. It is the largest province in Canada and has a surface area of 1,667,721 km^2, 46% of which is forested [25]. With a population of around 8.2 million inhabitants, who are overwhelmingly concentrated in the St. Lawrence River valley, Quebec's economy is highly integrated with Canadian and US economies.

Quebec's Capitale-Nationale region has 757,065 inhabitants—around 9% of the provincial population—and a surface area of 18,644 km^2, which yields a population density of 40.6 inhabitants km^{-2}. About 88% of the region's population live in Quebec City (the provincial capital), and 12% live in rural areas [26]. The region is predominantly forested, with about 15,014 km^2 or 80% of the region home to productive forests [27]. Forests under public tenure account for 70% of the region's forested area (versus about 92% for the province as a whole), while the rest of the forested land is privately owned [25]. The region is home to 75 forestry companies, about 45 of which are involved in harvesting and silviculture operations that operate mainly in public forests but also in private lots and provide wood for sawnwood, pulp, paper, and panel production. There are 10 pulp and paper mills in the region, which are responsible for about 2200 direct jobs, as well as 15 sawmills, 8 veneer, plywood, and reconstituted wood product mills, and 36 other wood product manufacturing plants, which account for about 1500 direct jobs [28]. There are approximately 15 bioenergy projects underway in the region, most of which are dedicated to heat and pellet production using residues from forest operations and wood processing [29–31].

2.2. Value Chain Topology

The Tool for Sustainability Impact Assessment (ToSIA) was developed to support the sustainability analysis and comparison of existing and theoretical forest product value chains, including forest biomass supply chains and bioenergy production systems [32,33]. It was designed to compare scenarios, calculate carbon flows through the value chain, and quantify environmental, economic, and social indicators. It has notably been used to evaluate how different scenarios can influence rural development and policy objectives [20,34–40]. ToSIA is a process-oriented tool, whereas other approaches such as the life cycle assessment, carbon footprint, and ecological footprint methods are product-based [41,42]. ToSIA lets users adjust the system's geographic boundaries and assessment focus, and is sufficiently flexible to permit combining multiple types of data [7,37]. It has been proven to be useful for supporting decision-making at the local and national levels [7,33,37,40].

Wood product value chains are simulated in ToSIA as processes grouped within modules. The flow of materials through the value chain is simulated as carbon units flowing from the forest to the end products, with specific input flows and output products for each process. Indicators are calculated in relation to each process and then multiplied by the quantity of material circulating in the process. As a result, ToSIA provides three types of information for each process: (i) the flow of materials in tons of carbon units, (ii) absolute indicator values, and (iii) relative indicator values, calculated as the ratio of the absolute indicator value to the units of material entering the process. These values can be aggregated by module in the value chain and for the whole value chain.

In this study, our assessment mainly consisted of comparing various forest bioenergy development scenarios in the Capitale-Nationale region using local wood resources. Wood chips generated by sawmills and wood pellets manufactured from sawmill processing residues are the bioenergy feedstocks most widely used in the region and were therefore chosen to form the basis of the analysis (Figure 1). Only the processes and flow of materials from commercial timber harvesting were considered; silvicultural activities not directly related to timber harvesting (e.g., planting, pre-commercial thinning, etc.) were ignored. Two timber harvesting methods are used in the region: whole-tree harvesting and cut-to-length harvesting [43]. Whole-tree harvesting is a practice in which trees are felled and transported to the roadside, where they are delimbed (see processes 2, 5, 6, and 7 in Figure 1). In cut-to-length harvesting, a multifunctional harvester head fells the tree, delimbs it, and cuts it into sections all at once; the logs are transported to the roadside afterward by a forwarder (see processes 1, 3, and 4 in Figure 1).

Wood chip value chains can have two main feedstocks: harvest residues from cutblocks, and roadside residues. Harvest residues from cutblocks include treetops, branches, and non-commercial tree stems or stem sections generated by cut-to-length harvesting operations performed in the forest. Residues from cutblocks can be collected and brought to a production site for chipping, in which case they are referred as "production site chips". Roadside residues include branches and tops generated during roadside delimbing as part of whole-tree harvesting operations; these residues are often chipped directly at the roadside (hereafter referred as "roadside chips"). Wood chips are ultimately sent to end users for heating or cogeneration (Figure 1).

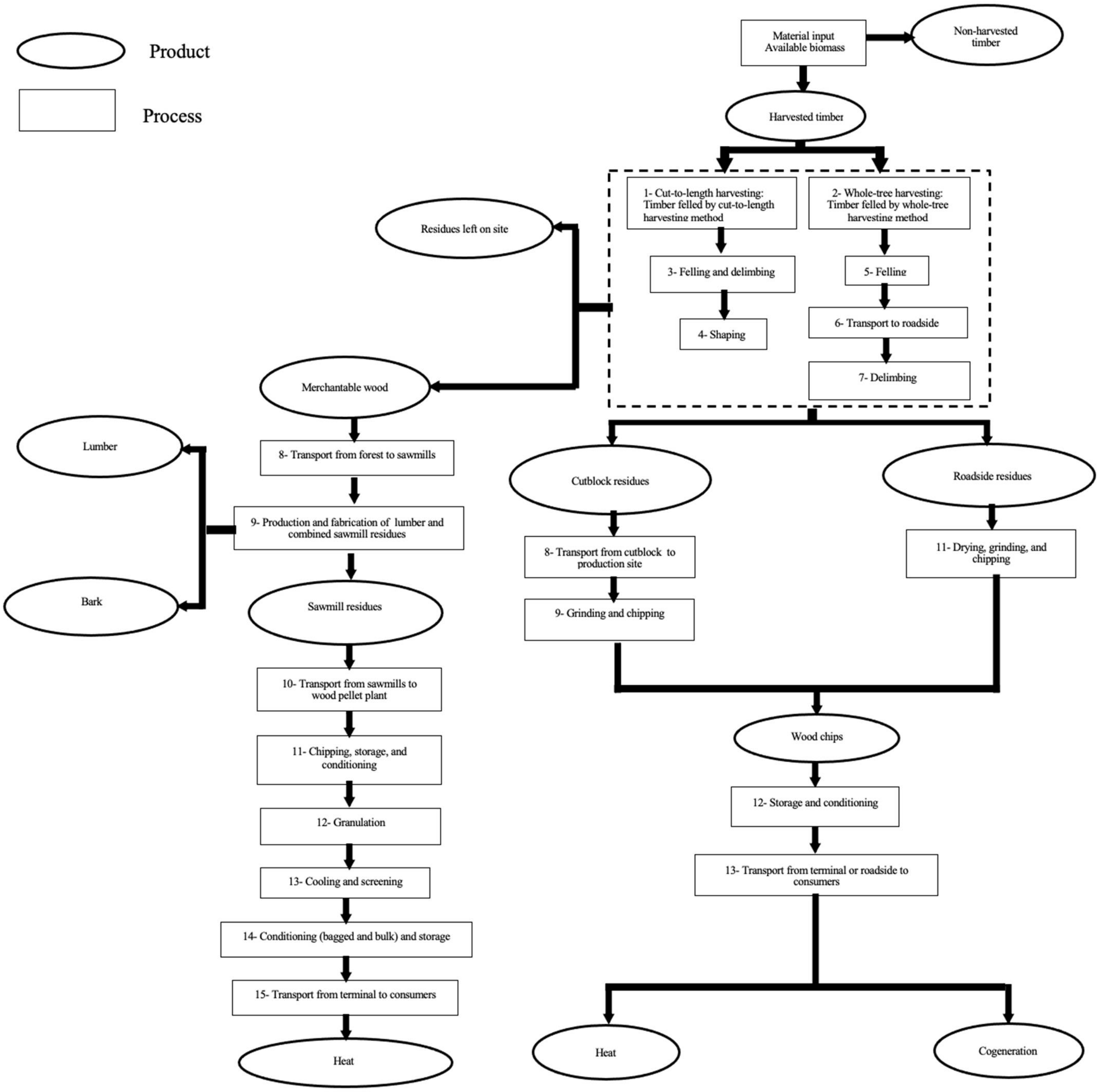

Figure 1. Simplified scheme of wood chip and wood pellet value chain topology in the Capitale-Nationale region.

In the Capitale-Nationale region, wood pellets are produced from sawmill residues obtained from wood processing plants [44]. The wood pellet value chain scheme shown in Figure 1 indicates that merchantable wood (i.e., wood intended for the manufacturing of solid wood products) is first transported from forest cutblocks to wood processing plants to produce and manufacture sawnwood products (processes 8 and 9). Then, residues such as sawdust and planer shavings are recovered and transported to pellet production plants (process 10) to manufacture pellets (processes 11, 12, 13 and 14). The final product is ultimately transported to end users for heating (process 15). Information on logistics and costs of transport was detailed in Locoh et al. [44].

2.3. Scenario Definition

2.3.1. Scenarios

First, a baseline scenario corresponding to the forestry and bioenergy situation in 2008 was defined (BaU2008). The year 2008 was chosen because it predates any significant policy push for forest bioenergy development in the province and data were available for the region in question for that year (Table 1). Approximately 712,000 oven-dry metric tons (odt) of wood [45] were harvested from public and private forests in 2008. About 61% of this wood was harvested using a whole-tree harvesting system, and the remaining roughly 39% was harvested using a cut-to-length system [43]. In 2008, 48% of the harvested volume was merchantable wood that was manufactured into wood products (including sawn products, panels, and boards), 25% was residues (5% harvest and 20% sawmill) that were used for energy production, and the remaining 27% was harvest residues that were left on the cutblock or roadside [46].

Table 1. Costs and subsidy amounts considered for 2008 and 2030, in US dollars (USD).

Description	2008BaU	2030HEAT	2030CHP	Data Sources
Cost of electricity (USD/kWh)	0.09			[47] [a]
Cost of natural gas (USD/kWh)	0.053			[47] [a]
Subsidies for heat production in buildings (USD/kWh)	-	0.101	-	[48] [b]
Subsidies for cogeneration production in buildings (USD/kWh)	-	-	0.101	[48] [b]

[a] Costs were converted to USD using http://www.banqueducanada.ca/taux/taux-de-change/convertisseur-de--devises-dix-dernieres-annees/ and adjusted to 2030 prices using this inflation calculator: http://www.usinflationcalculator.com (accessed on 5 May 2020). [b] Subsidies were converted to USD using http://www.banqueducanada.ca/taux/taux-de-change/convertisseur-de--devises-dix-dernieres-annees/ and adjusted to 2008 and 2030 prices using this inflation calculator: http://www.usinflationcalculator.com (accessed on 5 May 2020).

Then, other scenarios were defined to describe the potential evolution of the forest bioenergy sector until 2030 subject to various policy measures, biomass supply practices, and optimizing biomass feedstock and combustion technologies. The choice of the year 2030 was primarily dictated by Quebec's 2030 Energy Policy [23]. It also avoids distortions that much longer time horizons would create and that would lead to decisions being inconsistent with societal behavior.

- Policy measure scenarios

Three policy measure scenarios were defined for this study: the baseline scenario (2008BaU) describing the bioenergy situation in 2008 and two temporal projections for 2030 representing contrasting policy measures—one based on the promotion of heat production from forest biomass (2030HEAT) and one based on the promotion of combined heat and power production, i.e., cogeneration (2030CHP). In the 2008BaU scenario, it was assumed that subsidies would be proportionally provided based on the amount of heat and cogeneration production; however, there was no cogeneration in 2008 [47]. In the 2030HEAT scenario, subsidies were assumed to be solely provided to encourage converting existing fossil fuel-based heat production systems to forest biomass. For this reason, there are no subsidies for cogeneration production in that scenario. In the 2030CHP scenario, it was assumed that all available subsidies are allocated to cogeneration plants.

Table 1 shows the subsidy and cost variable values used in the three scenarios along with the sources those values were obtained from.

- Biomass supply and energy production scenarios

Four biomass supply and energy production scenarios were also defined in addition to the above policy measure scenarios: a business-as-usual (BaU) scenario, an increased biomass mobilization (B) scenario, an energy generation systems (S) scenario, and a harvesting methods (M) scenario (see Table 2). The B scenario represents an increase in the mobilization of available harvest and sawmill residues for conversion to wood chips or pellets for bioenergy production. The S scenario describes a situation in which the quality of the biomass feedstock and the feedstock requirements of conversion systems producing bioenergy are optimally matched. In the wood chip value chains, this was simulated by allocating chips made from production residues only to heating systems and chips made from roadside residues only to CHP systems. This scenario also includes an increase in sawmill residue mobilization for pellet production and heating to similar levels as in the B scenario. Finally, the M scenario describes an increase in whole-tree harvesting for timber production (and a corresponding decrease in cut-to-length harvesting), which implies that a larger share of harvest residues would be available at the roadside and subsequently chipped for bioenergy, and a smaller share of them would be collected from cutblocks and chipped at the production site.

Table 2. Scenarios and acronyms used.

	Biomass Supply and Energy Production Scenarios		Increased Biomass Mobilization	Harvesting Methods	Energy Generation Systems
Policy measure scenarios	Business-as-usual	2008BaU	2008B	2008M	2008S
	Subsidies for heat production in buildings	2030HEAT-BaU	2030HEAT-B	2030HEAT-M	2030HEAT-S
	Subsidies for cogeneration production in buildings	2030CHP-BaU	2030CHP-B	2030CHP-M	2030CHP-S

These four scenarios (BaU, B, S, and M) were applied in combination with the temporal references (2008 and 2030) and policy measures (HEAT and CHP). The acronyms used for the combinations are shown in Table 2.

2.3.2. Description of Scenarios

Table 3 shows the details of the scenarios used. Based on current practices (2020–2022) in the Capitale-Nationale region, it was assumed in this study that wood pellets are used only for heating and wood chips are used for both heating and cogeneration (CHP). The amount of residues collected from the different sources and mobilized in the value chains in the various scenarios used were based on wood production and residue generation estimates provided by experts and stakeholders of the forest biomass heating sector from the Capitale-Nationale region during interviews [44].

Table 3. Scenario details.

Scenarios		Wood Chips (Harvest Residues (odt))		Wood Pellets (Sawmill Residues (odt))	
		Production sites	Roadside		
BaU	2008	18,485	0	158,242	
	2030HEAT	297,424	127,467	272,232	
	2030CHP	297,424	127,467	-	
		Production sites	Roadside		
B	2008	424,891	0	193,406	
	2030HEAT	271,930	152,961	286,560	
	2030CHP	271,930	152,961	-	
		CTL	WTH	CTL	WTH
M	2008	11,282	7213	96,528	61,714
	2030HEAT	403,646	21,244	166,061	106,170
	2030CHP	403,646	21,244	-	-
		Production sites	Roadside		
S	2008	18,485	0	158,242	
	2030HEAT	399,398	0	272,232	
	2030CHP	0	25,493	-	

odt: oven-dry tonnes; WTH: whole tree harvesting; CTL: cut-to-length harvesting.

- Business-as-usual (BaU) scenarios
    1- Wood chips The baseline BaU scenario represents a picture of the Capitale-Nationale region's forest bioenergy sector in 2008. For the wood chip value chains in the 2008BaU scenario, wood chips for bioenergy were assumed to be produced only from production residues. In the BaU scenarios for 2030 (2030HEAT-BaU and 2030CHP-BaU), wood chips for bioenergy would come both from production residues (70% of the total annual wood chip supply) and roadside residues (30% of the total annual supply).
    2- Wood pellets For the wood pellet value chains in the 2008BaU scenario, available sawmill residues not already allocated to other products (such as pulp and paper or fiberboard) were assumed to be used for pellet production. In the 2030HEAT-BaU scenario, we assumed that about 95% of available sawmill residues would be allocated to pellet production.
- Increased biomass mobilization (B) scenarios
    1- Wood chips The B scenarios were defined to represent instances in which all available residues from timber harvesting are mobilized for bioenergy. In the 2008B scenario, this translated into an input of 424,891 odt of harvest residues for wood chip production (all production residues). In the B scenarios for 2030 (2030HEAT-B and 2030CHP-B), the total input of harvest residues for wood chip production would be the same as in the 2008B scenario but 64% was assumed to be production residues and the remaining 36% roadside residues. It was assumed that all wood chip production in the 2030HEAT-B and 2030CHP-B scenarios would be used only for heating and only for cogeneration, respectively.
    2- Wood pellets For the wood pellet value chains, the B scenarios represent instances in which a larger share of sawmill residues would be dedicated to wood pellet production. An input of 193,406 odt of residues were used in the 2008B scenario (corresponding to about 67% of total sawmill residues generated in the region) and 286,560 odt in the 2030HEAT-B scenario (corresponding to 100% of available sawmill residues).
- Harvesting methods (M) scenarios
    1- Wood chips The M scenarios reflect instances in which a higher proportion of timber harvesting would be whole-tree harvesting operations and a greater share of the residues used for bioenergy would thus be generated using this method. In the 2008M scenario, it was assumed that 61% of available harvest residues would be generated by whole-tree harvesting operations and the remaining 39% using the cut-to-length method. In the M scenarios for 2030 (2030HEAT-M and 2030CHP-M), 95% of the average annual amount of available harvest residues would be recovered from whole-tree harvesting operations and 5% from cut-to-length harvesting operations.
    2- Wood pellets For the wood pellet value chains in the 2008M scenario, 61% of sawmill residues generated by wood processing was assumed to come from timber harvested using the whole-tree harvesting method and 39% using the cut-to-length method. (Note that sawmill residues are used as feedstock for pellet production.) In the 2030HEAT-M scenario, 95% of the annual amount of sawmill residues generated by wood processing was assumed to come from timber harvested during whole-tree harvesting operations and 5% during cut-to-length harvesting operations.
- Energy generation systems (S) scenarios
    1- Wood chips In the S scenarios, it was assumed only wood chips made from production residues would be used in heat production systems and only those made from roadside residues would be used in cogeneration production systems. This means that in the 2008S scenario, wood chips made from production residues would be used to heat buildings. In the 2030HEAT-S scenario, it was assumed

that 94% of total available wood chips made from production residues would be mobilized. In the 2030CHP-S scenario, it was assumed that only wood chips generated from roadside residues would be used for cogeneration production; however, only 6% of roadside residues would actually be mobilized for this purpose.

2- Wood pellets The amount of sawmill residue used for pellet production in the 2008-S and 2030HEAT-S scenarios would be the same as in the 2008BaU and 2030HEAT-BaU scenarios, respectively.

2.4. Indicator Choice and Related Data

We chose the following environmental, economic, and social indicators in our study: greenhouse gas (GHG) emissions, air pollution, energy generation, employment, energy use, gross value added (GVA), and production cost. The indicators were selected from the ToSIA indicator framework [48] and represent standard sets that are often used in similar studies. The units, descriptions, and data sources for these indicators are listed in Table 4. The indicators were calculated manually for each process in accordance with the instructions in the ToSIA indicator data format requirements [49].

Table 4. Indicator details and data sources.

Indicators	Units	Description	Data Sources
		Environmental indicators	
Greenhouse gas (GHG) emissions	Kg CO_2 -eq	GHG emissions are reported as carbon dioxide (CO_2) equivalents and calculated according to IPCC guidelines [50]. They were estimated based on the Global Warming Potential (GWP) metric over 100 years of direct GHG emissions from fuel combustion for harvesting and transport, and of direct GHG emissions from wood combustion for energy generation.	[50]
Air pollution	Kg	The air pollution indicator is assessed by quantifying five non-GHG emission indicators—fine particulate matter (PM10), carbon monoxide (CO), nitric oxide or nitrogen monoxide (NO_x), sulfur dioxide (SO_2) and non-methane volatile organic compounds (NMVOC). PM10 emissions depend on the type of energy production system and biomass used.	
		Economic indicators	
Gross value added (GVA)	USD	"Gross value added" is defined as the gross amount of added value remaining in the Capitale-Nationale region at a given point in time, in USD. It is calculated using the following formula: GVA = consumer price of finished product − production costs + subsidies [40].	[51]
Energy generation	GWh	"Energy generation" is defined as heat and electricity generation from harvest and sawmill residues.	[52]
		Social indicators	
Employment	Full-time equivalents per year	The employment indicator is reported as the absolute number of full-time equivalent workers per year that can be allocated to a specific process.	[53]
Energy use	KWh	The energy use indicator reports direct fossil fuel and electricity use. It is an environmental indicator, but it also affects economic performance through production costs, especially labor costs. Labor costs are the costs incurred by an employer in the employment of labor and include remuneration for work performed, paid time not worked, bonuses, gratuities, employers' social security expenditures, and costs incurred by the employer for vocational training [54]. In this study, it is considered a social indicator.	[47]

3. Results

3.1. Environmental Indicators

3.1.1. GHG Emissions

In the wood chip value chains (Figure 2A, left panel), the highest total GHG emissions from harvesting and transport are associated with the M scenarios, in which there is an increase in the use of whole-tree harvesting. Compared to the baseline (BaU) scenarios, the M scenarios show a roughly 4% increase in GHG emissions, while the B scenarios show a 2% increase. However, emission levels in the S scenarios are similar to those in the BaU scenarios.

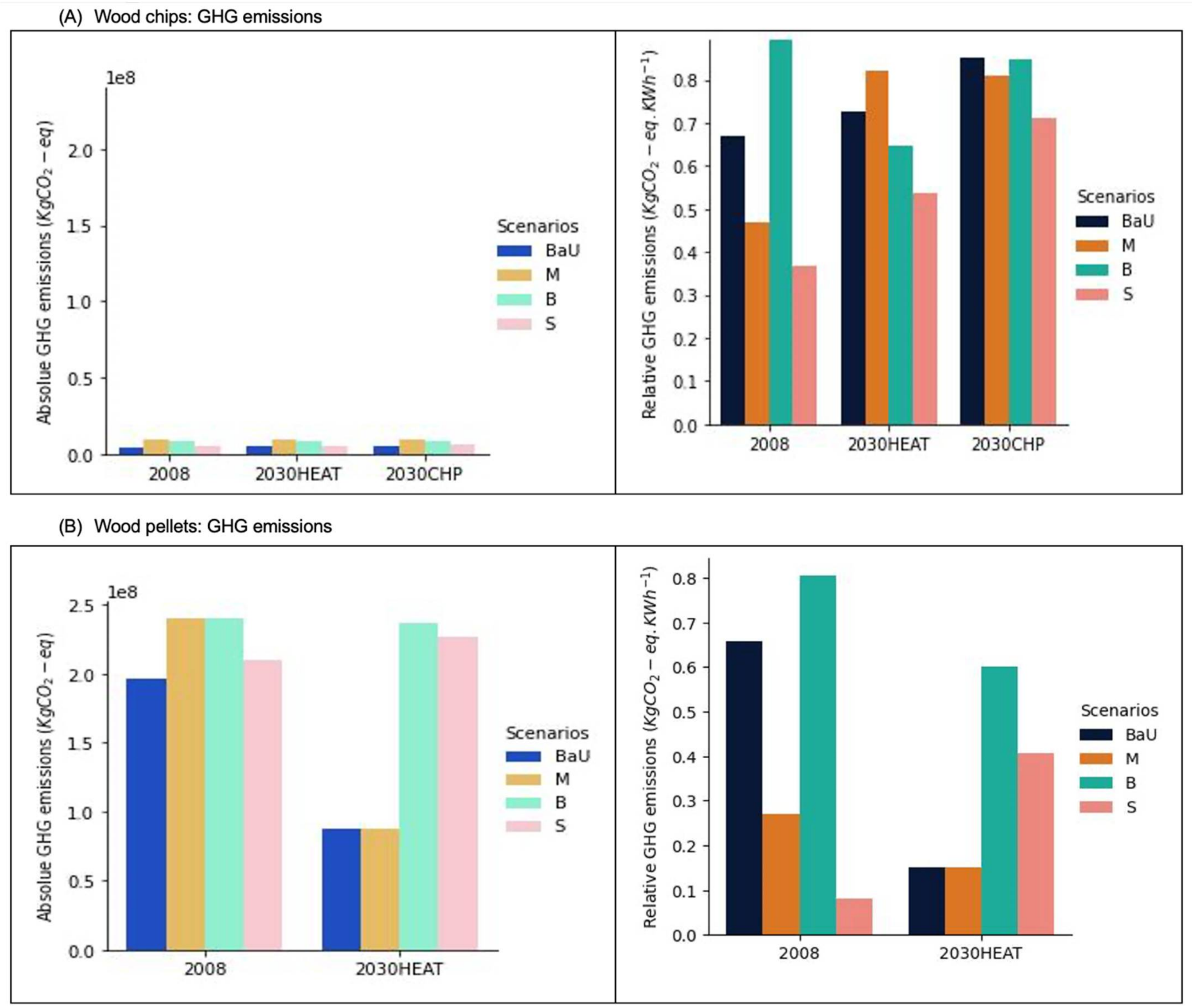

Figure 2. GHG emissions from fossil fuels generated during harvesting and transport for wood chip (**A**) and wood pellet (**B**) value chain scenarios. (**Left panel**): Absolute GHG emissions from harvesting and transport, expressed in kg of CO_2 equivalent. (**Right panel**): Relative GHG emissions from harvesting, transport, and combustion, expressed in kg of CO_2 equivalent emitted per kWh of energy produced.

In the wood pellet value chains (Figure 2B, left panel), overall GHG emissions from harvesting and transport are highest in the B scenario in which biomass is used for heat production (2030HEAT-B).

The relative GHG emissions indicator (Figure 2B, right panels) represents the amount of GHG emissions from harvesting, transport, and combustion generated to produce 1 kWh of bioenergy. Relative GHG emissions are lower for wood pellets (Figure 2B, right panel) than for wood chips (Figure 2A, right panel) in all scenarios. Also, relative emissions tend to be lower for the value chains in which biomass feedstock and conversion technologies are optimally matched (S scenarios) than those in the other scenarios, except in the case of wood pellets in 2030, for which relative emissions are the lowest in the BaU and the M scenarios. Conversely, relative emissions tend to be highest in the B scenarios.

3.1.2. Air Pollution

- CO, NMVOC, NO_x, and SO_2 emissions The impacts wood chip and wood pellet value chains have on air pollution were determined using five non-GHG emission indicators that are expressed as a percentage of 2008BaU emissions (Figure 3). The impacts of the various scenarios were mixed, with no clear pattern in the effect of the biomass supply and energy production scenarios. Nevertheless, most 2030 scenarios seem to show an increase in NOx emissions relative to the 2008BaU scenario (except for the 2030HEAT-S and -B scenarios for the wood pellet value chains) and a relative decrease in CO and SO_2 emissions (except for the 2030HEAT-B scenario, which causes a relative increase in CO for both value chains). Most 2030 scenarios cause either no change or a relative decrease in NMVOC.

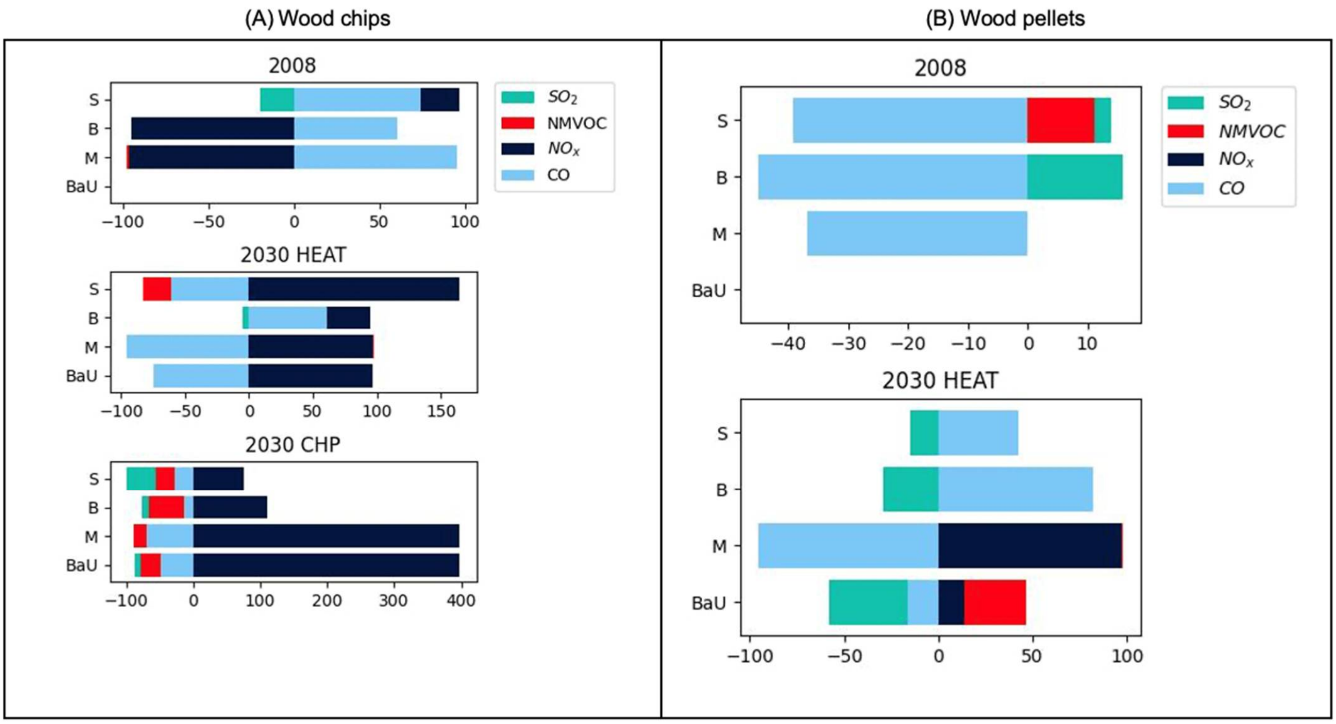

Figure 3. Non-GHG (CO, NMVOC, NO_x, and SO_2) emissions for wood chip (**A**) and wood pellet (**B**) value chain scenarios, expressed as a percentage of 2008BaU emissions.

- Particulate matter emissions

For the wood chip value chains, PM10 emissions generally decrease in both absolute and relative terms (Figure 4A, left and right panels, respectively) in the 2030 scenarios compared with the 2008 scenarios. However, the decrease is less pronounced in the 2030HEAT-B scenario and more pronounced in the 2030CHP-B scenario. Also, the 2030CHP-S scenario shows the largest decrease compared with its 2008 reference (the 2008S scenario).

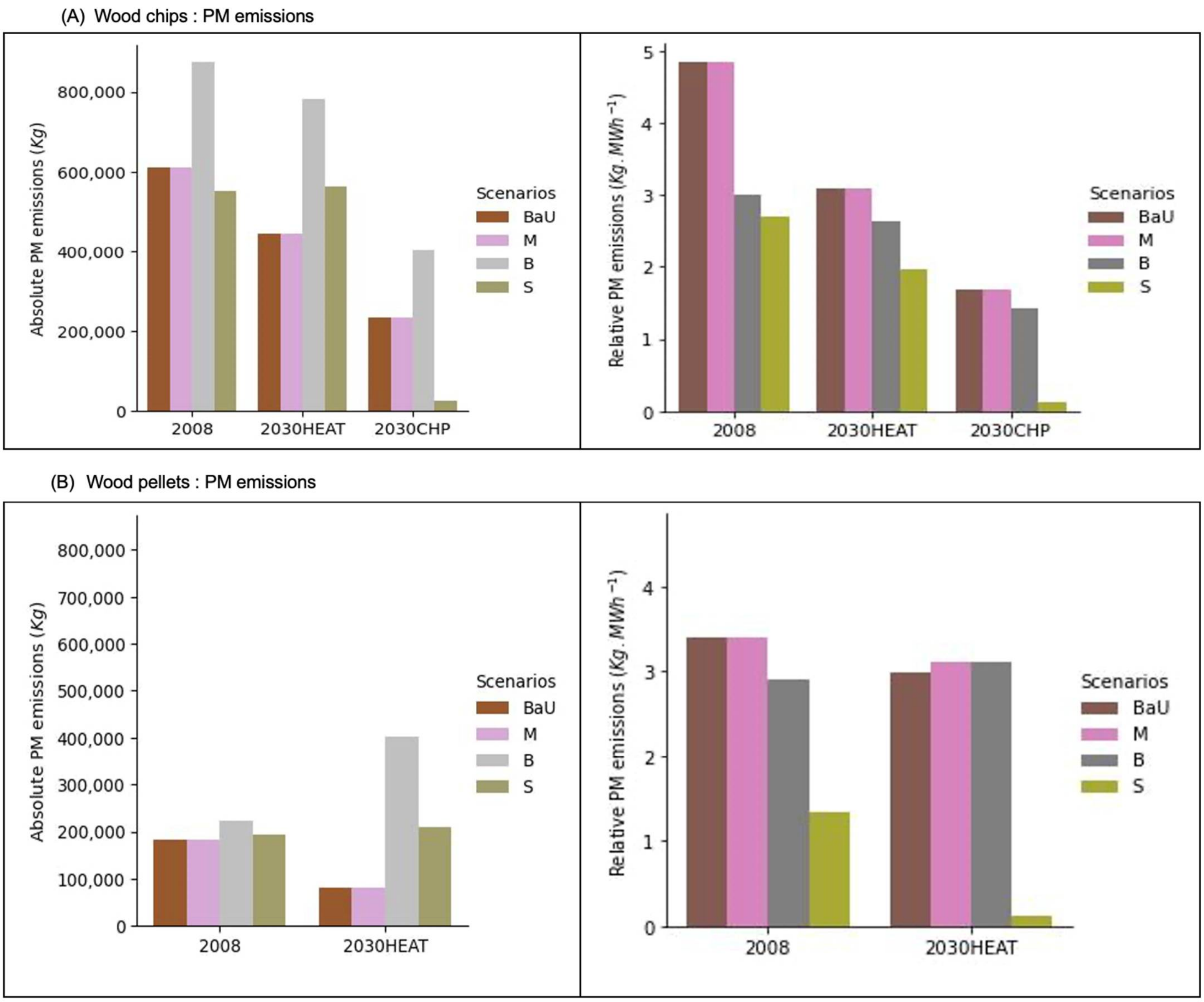

Figure 4. Particulate matter (PM) emissions for wood chip (**A**) and wood pellet (**B**) value chain scenarios. Left panel: absolute PM emissions, expressed in kg of PM emitted. Right panel: relative PM emissions, expressed in kg of PM emitted per kWh of energy produced.

For the wood pellet value chains, while absolute PM10 emissions decrease in 2030 for the BaU and M scenarios, they increase in the 2030HEAT-B and 2030HEAT-S scenarios compared with their 2008 references (2008B and 2008S, respectively) (Figure 4B, left panel). As for relative PM10 emissions, all 2030 scenarios show a decrease compared with their respective 2008 references, except for 2030HEAT-B, which shows an increase.

3.2. Economic Indicators

3.2.1. Gross Value Added (GVA)

The GVA indicator has a positive value for all wood chip value chain scenarios (Figure 5A). Despite subsidies for heat and cogeneration production, GVA remains positive in all scenarios. Moreover, GVA is higher in the 2030 scenarios than in the 2008 scenarios, averaging $13 million in 2008 and $27 million in 2030. The 2030CHP-B scenario has the highest GVA of the 2030 scenarios.

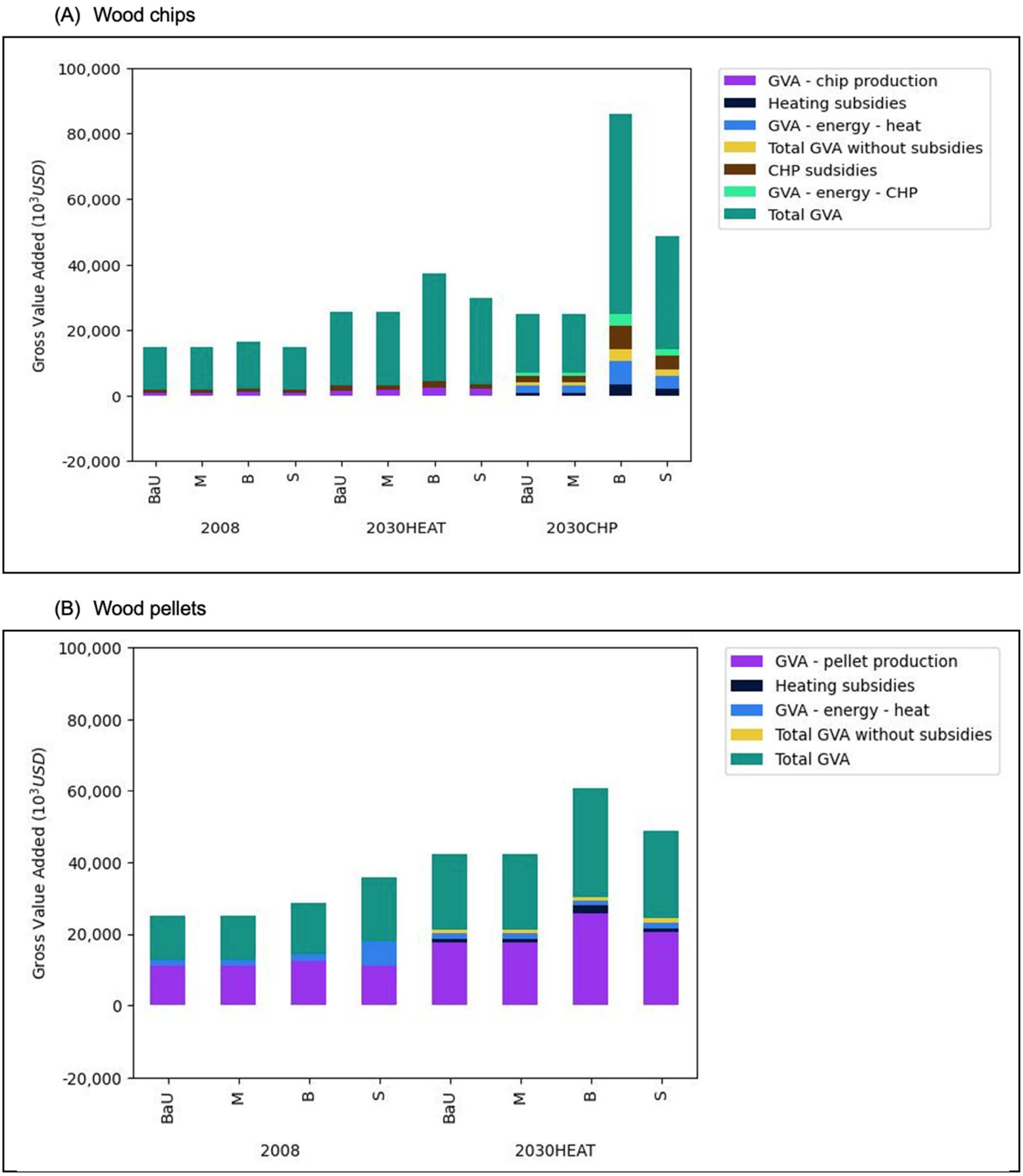

Figure 5. Gross value added for wood chip (**A**) and wood pellet (**B**) value chain scenarios, expressed in US dollars (USD).

In the wood pellet value chain scenarios (Figure 5B), the GVA indicator again shows a positive value for all scenarios considered, with or without heating subsidies. The 2030HEAT-B scenario has the highest GVA.

To evaluate the impact of energy generation system efficiency on economic performance, a sensitivity analysis was conducted by testing the effect of different levels of combustion efficiency (i.e., how efficiently an energy generation system converts biomass feedstock (chips or pellets) into usable energy) on GVA. For the wood chip value chain, a minimum of 80% combustion efficiency was required in the 2030HEAT scenarios to achieve a positive GVA value due to subsidies for heat production. However, about 38% combustion efficiency resulted in a positive GVA value in the 2030CHP scenarios because electricity prices would increase more than wood chip prices compared to their 2008 values. For the wood pellet value chain, the sensitivity analysis suggests that 75% combustion efficiency is required to obtain a positive GVA value.

3.2.2. Energy Generation

For wood chip value chains, heat production from biomass reaches approximately 30 GWh year^{-1} in the 2008BaU scenario (Table 5). The 2008B scenario has the highest heat production value (around 89 GWh year^{-1}) of the 2008 scenarios due to its higher biomass mobilization. Among the 2030 scenarios, the 2030HEAT-B and 2030CHP-B scenarios have the highest heat production values (roughly 726 and 373 GWh year^{-1}, respectively) with full mobilization of available biomass (Table 5). The 2030HEAT-BaU and 2030HEAT-M scenarios produce the same amount of heat—roughly 581 GWh year^{-1} (Table 5)—without any increase in biomass mobilization. The 2030CHP-BaU scenario produces 437 GWh year^{-1} more heat than the 2008BaU scenario, which is an increase of 1466%. The 2030HEAT-BaU scenario produces 1847% more heat than the 2008BaU scenario. There is a slight increase in the total energy (heat and electricity) produced in 2030 when feedstock is optimized for energy generation in cogeneration systems (the 2030CHP-S scenario) compared to the 2030CHP-BaU scenario.

Table 5. Heat and electricity production for wood chip and wood pellet value chain scenarios.

Scenarios		Wood Chips (GWh Year^{-1}) Heat	Wood Chips (GWh Year^{-1}) Electricity	Wood Pellets (GWh Year^{-1}) Heat
2008	BaU	29.839	0	155.981
	M	29.839	0	155.981
	B	88.621	0	190.643
	S	25.927	0	155.981
2030HEAT	BaU	580.947	0	693.248
	M	580.947	0	693.248
	B	726.493	0	735.624
	S	559.682	0	693.248
2030CHP	BaU	355.098	112.249	-
	M	355.098	112.249	-
	B	372.812	202.065	-
	S	293.361	183.148	-

For wood pellet value chains, 155 GWh year^{-1} of heat is produced in the 2008BaU scenario (Table 5). The 2008B scenario has the highest heat production value (190 GWh year^{-1}) of the 2008 scenarios. Among the 2030HEAT scenarios, the 2030HEAT-B scenario has the highest heat production value, 735 GWh year^{-1}, which is an approximately 286% increase compared with the 2008B scenario when all available biomass is mobilized for heat production.

3.3. Social Indicators

3.3.1. Employment

For wood chip value chains, employment levels vary from one scenario to the next (Figure 6A). Increased biomass mobilization in the 2008B scenario results in a 22% increase in employment compared to the 2008BaU scenario. Conversely, a change in the harvesting method (increased use of whole-tree harvesting relative to cut-to-length harvesting) in the 2030HEAT-M and 2030CHP-M scenarios decreases the employment indicator value in those scenarios by roughly 12% compared to the baseline scenario (2008M). The increased biomass mobilization simulated in the 2030HEAT-B and 2030CHP-B scenarios leads to an approximate 50% increase in employment compared with the 2030HEAT-BaU and 2030CHP-BaU scenarios. A change in harvesting methods leads to an approximate 50% drop in employment in the 2030HEAT-M and 2030CHP-M scenarios compared to the 2008BaU scenario (Figure 6A). Feedstock optimization for energy generation systems in the S scenarios leads to an approximate 45% drop in employment compared to the 2008BaU scenario (Figure 6A).

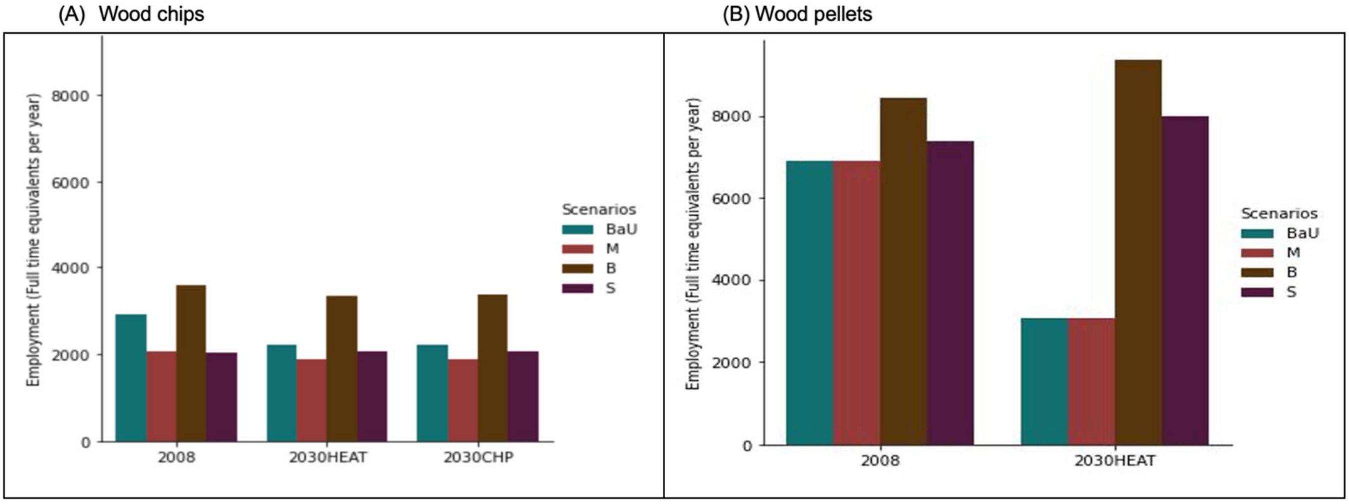

Figure 6. Employment levels for wood chip (**A**) and wood pellet (**B**) value chain scenarios, expressed in full-time equivalents per year.

Biomass mobilization is also a key variable for employment in wood pellet value chains (Figure 6B). Increased biomass mobilization in the 2008B scenario leads to an increase in employment compared to the 2008BaU scenario. In 2030, increased biomass mobilization (in the 2030HEAT-B scenario) and feedstock optimization for energy generation systems (in the 2030HEAT-S scenario) lead to an over 50% increase in employment in those scenarios compared to the 2008B and 2008S scenarios, respectively.

3.3.2. Energy Use

Figure 7 compares relative fossil fuel energy consumption per unit of bioenergy produced, which provides an indicator of the efficiency of energy production among value chains and scenarios.

For both wood chip and wood pellet value chains, increased biomass mobilization (in the B scenarios) increases the relative amount of fossil fuel energy consumed. However, an increase in whole-tree harvesting (in the M scenarios) and feedstock optimization for energy generation systems (in the S scenarios) both lead to a decrease in the relative amount of fossil fuel energy consumed. For example, 26% less fossil fuel energy is consumed in the 2030HEAT-M scenario than in the 2030HEAT-BaU scenario, and roughly 33% less fossil fuel energy is consumed in the S scenarios than in their corresponding BaU scenarios (Figure 7).

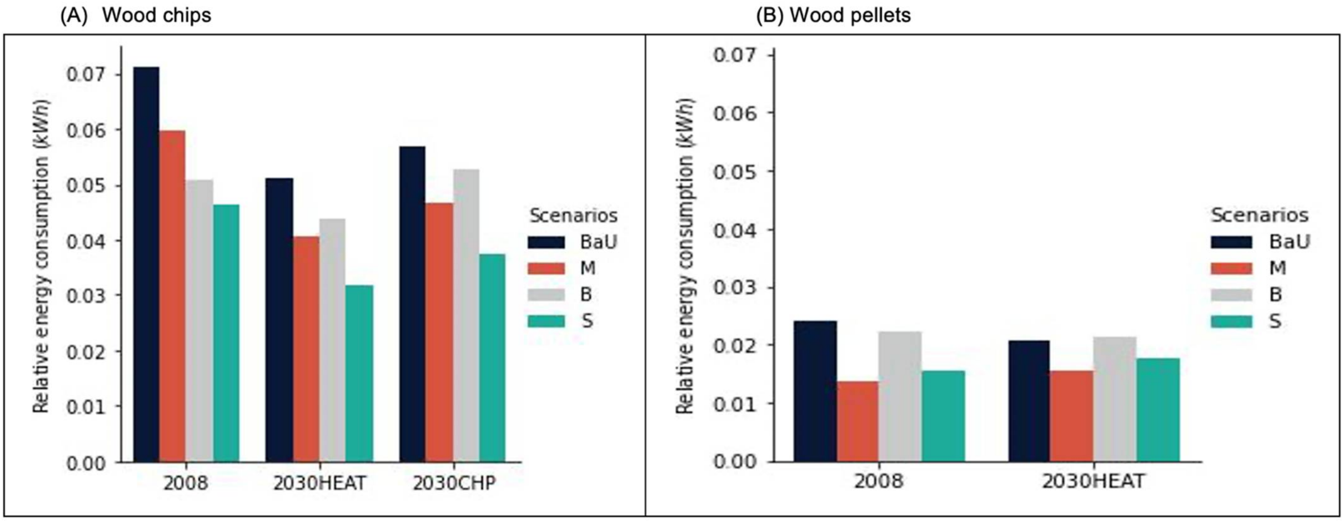

Figure 7. Relative fossil fuel energy consumption for wood chip (**A**) and wood pellet (**B**) value chain scenarios, expressed in kWh of fossil fuel energy consumed per bioenergy generated.

4. Discussion

The Quebec Association for the Production of Renewable Energy (AQPER) developed a renewable energy roadmap for Quebec that estimates that the province must generate 96 petajoules (PJ) of bioenergy by 2030 to meet its energy transition and climate action goals, and 17 of those 96 PJ should take the form of solid biomass for heating. Our research highlights the sustainability aspects of deploying forest biomass value chains for heat and cogeneration production in institutional and commercial buildings in 2030, using a case study of the Capitale-Nationale region. This region is home to about 3.7% of the province's productive forest area and 4.2% of its standing merchantable wood [27]. With a significant increase in biomass mobilization (in the B scenarios) by recovering additional residues from cutblocks, roadsides and sawmills, the region could produce up to about 4.4 PJ of bioenergy for heating or 3.5 PJ of bioenergy for cogeneration from wood chips in 2030. In contrast, only 0.5 PJ of bioenergy for heating was produced in 2008. Similarly, up to 4.5 PJ of bioenergy for heating could be produced from wood pellets in 2030, whereas only 1.2 PJ of bioenergy for heating was produced in 2008. This suggests that Quebec's target of 17 PJ by 2030 appears achievable with coordinated policy and logistical efforts across the province. Quebec already relies on a mature and structured forest industry with a trained workforce. The government has also enacted over the years policies and strategies aimed at the optimization of forest resources and the development of new products, including bioenergy and bioproducts [55]. The likelihood that biomass feedstock can be mobilized for energy production over the next years, given that the right policies and actions are put in place, is, therefore high.

Various policy measures and changes in biomass supply chains and energy generation systems could help to achieve different policy aims. Table 6 summarizes the policy aims and whether the scenarios considered would contribute positively or negatively toward those aims. Our study suggests replacing less efficient fossil fuel-consuming heat and cogeneration plants with biomass plants would promote economic development. Increased biomass mobilization could also help achieve policy targets such as increased renewable energy production, employment, and wealth creation in communities. However, this policy per se does not lead to a reduction in air pollutant emissions. Nevertheless, replacing less efficient fossil fuel-consuming heat and cogeneration plants with forest bioenergy-based plants whose feedstock is optimized for energy generation systems (in the S scenarios) would lead to a reduction in GHG emissions and some non-GHG (e.g., PM10) emissions.

Table 6. Summary of policy aims and actions the scenarios considered were based on. * and † indicate that the action positively addresses the policy aim in question (* for wood chips value chain and † for wood pellets value chain), and × indicates that the action negatively addresses it.

Actions Policy Aims	Increased Biomass Mobilization	Construction of Efficient Heat Plants	Construction of CHP Plants	Replacement of Less Efficient Plants
Increase the availability of heat from renewable resources	* †	* †		
Increase regional income	* †		*	*
Increase employment	* †			
Minimize GHG and air pollutant emissions	×			* †

The results are analyzed below by aspect of sustainability they touch on (environmental, economic, and social).

4.1. Environmental Aspects

Our results suggest that increased biomass mobilization (in the B scenarios) leads to an increase in GHG (i.e., CO_2, CH_4, and N_2O) emissions. Our estimates of the amount of GHG emissions feedstock harvesting and transport and biomass combustion generate per unit of bioenergy produced are higher than the amounts we retrieved from GHGenius for propane and oil supply and production chains. For example, wood chips used for heat production generated between 27.53 and 96.4 $MgCO_2/MJ$ of GHG emissions in the 2008 scenarios, whereas the production and use of propane and light oil generated 22.4 and 15 $MgCO_2/MJ$ of GHG emissions, respectively, according to GHGenius [56]. The higher emissions associated with bioenergy are due to the lower energy density of organic material relative to fossil fuel-based energy sources, which causes higher GHG emissions at the stack. This fact has been well documented [57]. Therefore, forest biomass systems can generate more initial emissions than their fossil fuel-based counterparts, which is often called a "carbon debt" and delays GHG emission reductions associated with a transition to renewable energy. However, over time, this debt is usually "reimbursed," and forest biomass systems start providing GHG emission reduction benefits. The time to reimbursement is especially quick in residue-based value chains [58].

Biomass use also contributes to fine particles and other atmospheric pollutant emissions during combustion. Increased biomass mobilization leads to greater emissions, which can significantly impact air quality. Estimates show that these emissions could be reduced at the source by 2030 with biomass feedstock and energy system optimization requirements. Optimizing biomass feedstock and combustion technologies leads to fewer fine particles and other air pollutants (SO_2, NO_x, CO, and NMVOC) being emitted. To achieve this, performance standards and regulations must promote the use of appropriate equipment. In Quebec, combustion system emission standards are based on the Canadian Standards Association's Standard CSA-B415.1. Newly developed biomass combustion systems have been subject to it since 2009. It recommends that all EPA-certified wood-burning appliances that have been independently tested by accredited laboratories must comply with the following particulate emission limits: 7.5 g/h for non-catalytic wood boilers and 4.1 g/h for catalytic wood boilers [59]. Nitrous oxide (NO_x) comes mainly from transportation. Reducing the distances woody materials are transported may contribute to reducing NO_x emissions. The negative correlation between energy production technology efficiency and fine particle emissions implies that long-term improvements in combustion efficiency could have a twofold impact, resulting first in an increase in forest bioenergy production, especially for heating purposes, and second in fewer pollutant particles in the air. While increased biomass mobilization could lead to higher pollutant emissions, in the Capitale-Nationale region, feedstock and combustion technology optimization (in the S scenarios) can reduce PM10 emissions by roughly 20%, SO_2 emissions by 90%, CO emissions by 25%, and NMVOC emissions by 65%.

4.2. Economic Aspects

The optimization of biomass feedstock and energy system requirements combined with increased biomass mobilization can contribute to increasing the Capitale-Nationale region's heating and cogeneration production. Decision-making must consider factors beyond the cost of technology, like fuel prices, boiler efficiency, and boiler performance, along with the energy density of the biomass type chosen. Our study suggests that heating subsidies can increase the value added to energy generation processes with a combustion efficiency rate of approximately 55%. Economic performance without subsidies remains positive if somewhat diminished. The implication is that subsidies reduce production costs and consequently decrease the price of bioenergy feedstock. Thus, in the absence of subsidies, an increase in bioenergy production for building heating would have a positive, if somewhat smaller, impact on the region's economy. On the other hand, while cogeneration positively impacts the region's economic performance, the profitability of cogeneration production would have to be ensured over the long term. Combining bioenergy with other types of energy (e.g., hydroelectricity, wind power) could ensure its long-term continuity and profitability [60–62].

Previous studies corroborate these findings about the long-term economic profitability of building heat production. However, while subsidies promote the use of forest bioenergy for heating purposes, their impact quickly diminishes when taxes are applied [63]. Economists advocate using a fossil fuel tax when public interventions seek to reduce GHG emissions. This policy increases the price of fossil fuels and thus reduces consumption. However, incentivizing forest bioenergy use through subsidies could reduce fossil fuel use in the long term if biofuel prices decrease due to lower production costs [64,65].

Energy consumption is one of the environmental indicators that influence sustainability. Indeed, the results show that highly efficient energy production (in the S scenarios) reduces energy consumption. However, increased biomass mobilization (in the B scenarios) leads to an increase in energy consumption. Therefore, efficient and effective energy production systems could reduce energy consumption. Also, improved harvesting methods could reduce fossil fuel consumption and thus increase the demand for bioenergy [66,67].

Our sensitivity analysis suggests that combustion efficiency must be about 80% for heating systems and 38% for cogeneration systems in wood chip value chains, and 75% for heating systems in wood pellet value chains to obtain a positive GVA. Studies on the efficiency of forest biomass conversion systems show that these values are achievable because conversion efficiency is an equipment-dependent [67]. Currently, available wood chip conversion technologies for cogeneration can achieve about 85% efficiency overall. Given their efficiency, it is recommended to use fluid bed boilers (75–92% efficiency) rather than fixed bed boilers (60–90% efficiency) for heating [68]. For their part, wood pellet boilers can achieve 90% efficiency for heating [69].

4.3. Social Aspects

Unsurprisingly, our study suggests that increased biomass mobilization leads to an increase in employment. Conversely, improved harvesting methods and optimizing biomass feedstock and combustion technologies result in fewer available jobs in the short term but more jobs in the long term. Similarly, other studies have found that bioenergy production creates direct, indirect, and induced employment [70]. Declining employment levels resulting from improved harvesting methods and optimized combustion technologies could potentially impact jobs in bioenergy production, including heat and cogeneration plant construction operations, conversion plant operation and maintenance, and biomass transportation. Yet, overall bioenergy production should be up by 2030 due to increased use of forest biomass and better optimization of biomass feedstock and energy system requirements.

As compared with the B and S scenarios for 2030 (2030HEATt-B, 2030CHP-B, 2030HEAT-S, and 2030CHP-S), the 2008B and 2008S scenarios show that feedstock optimization for energy production systems and increased biomass mobilization have a positive impact on energy production. An increase in the amount of energy produced could be accompanied by an increase in the amount of biomass mobilized. Thus, increased biomass mobilization could be an action that has a multiplier effect on indirect job creation and income opportunities [10,71].

5. Conclusions

This study compared the ability of wood chip- and wood pellet-based bioenergy value chains to meet institutional, commercial, and industrial energy needs such as heat and cogeneration production in the Capitale-Nationale region of Quebec. Our projections suggest that significant forest biomass mobilization combined with the implementation of efficient biomass feedstock and combustion technologies are key factors for the region that could contribute significantly to achieving the province's renewable energy and bioenergy production targets. Transitioning existing heat production systems from fossil fuel to forest biomass, when combined with more heating and cogeneration plants, could help create added value at the regional level. But only significant forest biomass mobilization will increase employment levels. As for environmental issues, feedstock quality optimization for bioenergy systems could reduce GHG and fine particle emissions and reduce the amount of fossil energy inputs needed.

For both wood chip and wood pellet value chains, the gross value added remains positive even in the absence of bioenergy subsidies. Overall, bioenergy use yields slightly better economic results for heat production than for cogeneration production. This is likely due to Quebec's specific energy portfolio, in which affordable renewable electricity is already abundant but still highlights the crucial role forest biomass could play for heating needs.

Conducting a sustainability impact assessment on the entire forest bioenergy sector is often difficult, even at the regional and local levels, due to the number of complex interactions involved. One of the main limitations of our study involved the diversity and processing of the data sources used. Indeed, secondary data from national statistics and institutions do not always shed light on the specific value chain processes. Moreover, the analysis conducted in this study excludes the sustainability impact of roundwood products and does not consider the impact of competing materials. Nevertheless, ToSIA offers a transparent approach when it comes to documenting assumptions and representing the most relevant value chain processes and provides a baseline for monitoring the impacts of future actions. A sustainability analysis of the entire forestry sector could help tackle specific questions related to the harmonization of forest biomass supply chains with larger forest management and wood production activities and help to identify potential synergies within the sector. Future research could also focus on the collection of standardized data on biomass feedstock availability and use for energy production and on the economic, environmental, and social outcomes of bioenergy, which will provide insights into the actual efficiency of policy measures at mobilizing forest bioenergy.

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