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Industrial Electrification Potential for Decarbonization in Quebec

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Abstract. Electrification of Quebec's industrial sector is a key decarbonization pathway in the context of its already low-carbon electricity supply. This study assesses the electrification potential of thirteen energy-intensive sub-sectors: primary aluminum, pulp and paper, steel, cement, alumina, lime, petroleum refining, iron ore mining and pelletizing, gold and silver mining, chemicals, agrifood, non-ferrous metals refining and smelting, and wood products. Based on a bottom-up analysis of fossil fuel consumption by process and equipment based on 2019 data, and an evaluation of electro-technology applicability as a function of process temperature, two scenarios are examined: a techno-optimistic scenario assuming full electrification regardless of technology maturity, and a high-TRL scenario limited to commercially available or near-commercial solutions. Low- and medium-temperature processes (<700 °C) show high electrification potential using mature technologies such as heat pumps, electric boilers, and resistance heating, whereas high-temperature processes depend on more capital-intensive and process-specific solutions, including electric furnaces, plasma technologies, and hydrogen-based pathways. In the techno-optimistic scenario, fossil fuel consumption, GHG emissions, and electricity use change by -85%, -51%, and +53%, respectively for the thirteen sub-sectors, while in the high-TRL scenario they change by -44%, -21%, and +28% respectively. The associated annual energy cost increases are estimated at C$656 million and C$254 million for the two scenarios, respectively. Overall, electrification requires major investments in electro-technologies and their process integration, and electricity generation and transmission infrastructure; it can substantially reduce GHG emissions but cannot eliminate a significant share of process emissions.

Keywords: Electrification, Industry Energy Demand, Industry Decarbonization

1. Introduction

The industrial sector in Quebec accounted for more than 39% of the province's total energy consumption in 2019, contributing 35% of its GHG emissions for that year [1], [2]. Therefore, decarbonization of this sector plays a crucial role in meeting the provincial net-zero emissions goal for 2050 [3]. Industrial decarbonization strategies in Quebec include energy efficiency, electrification, use of renewable energy sources like bioenergy and green hydrogen, and carbon capture and storage technologies [4]. However, implementing these measures may face challenges including technical and process-specific barriers, high capital costs and investment risks, biomass availability, electricity availability and increased peak demand, technology readiness limitations, and infrastructure and supply-chain constraints [5], [6].

Given that electricity production in Quebec is mainly hydroelectric (94% of total production in 2021) and therefore has no significant impact on emissions, it is highly advantageous to prioritize electrification as a major decarbonization strategy in this province [7]. In general, electricity-powered energy systems are more efficient than those powered by fossil fuels. Thus, electrifying end-use energy demand would have the dual benefit of reducing future energy demand and reducing GHG emissions.

However, there is scarce provincial-level data on what fraction of industrial fossil fuel consumption could be replaced through electrification, how much GHG emissions would be reduced, and how much electricity would then be consumed, be it using commercially available electro-technologies, or less mature ones longer-term. Such data, even with limited accuracy, would be useful to provide policymakers, utilities and other stakeholders with a quick assessment of the industrial electrification potential and the possible consequences on the provincial energy system. Thus, there is a need to provide such estimates without requiring engineering studies to estimate capital expenditures, or energy systems modelling to predict emissions trajectories in detail.

This study assesses the electrification potential of various industrial processes in thirteen industrial sub-sectors in Quebec using publicly available data for 2019. Collectively, these thirteen sub-sectors accounted for more than 72% of Quebec's total industrial energy consumption, more than 68% of its total GHG emissions, over 61% of its total industrial fossil fuel consumption, and over 62% of its total GHG emissions from fossil fuels in 2019. They represent even larger percentages of what is generally understood as heavy industrial. [2], [7], [8], [9], [10]

Estimating a sectoral electrification potential involves quantifying the annual consumption of fossil fuel that could be replaced by electricity, as well as the corresponding annual electricity demand. This quantification depends on a detailed breakdown of energy consumption by the type of equipment, the type of fuel, operating temperature, and end-use category.

Electrification faces inherent constraints in applications where fossil fuels serve as non-energy feedstocks or where combustion is fundamental to the underlying process. Nonetheless, emerging technologies, including molten oxide electrolysis, electrolytic hydrogen, and inert-anode aluminum production, offer promising pathways for overcoming these limitations [11].

It should be noted that this study quantifies the potential for electrification independently of other decarbonization measures (e.g., energy efficiency or bioenergy use). The practical potential for electrification depends on the relative merits of each measure for each process, which is beyond the scope of this study.

2. Methodology

The methodology used to assess the electrification potential of industrial processes is based on a set of simplifying assumptions, at it aims only at quantifying the annual energy consumption effects of electrifying Quebec's industrial sector as it currently operates. The analysis does not consider variations in production levels, the deployment of new infrastructure or capital investments, or prospective improvements in technological efficiency. The performance parameters assigned to fossil fuel-based processes and candidate electrical technologies reflect current technological knowledge. In addition, Quebec's electricity supply is assumed to be entirely decarbonized. As illustrated in **Figure 1**, the electrification assessment framework is structured around four main steps, which are described in the following sections.

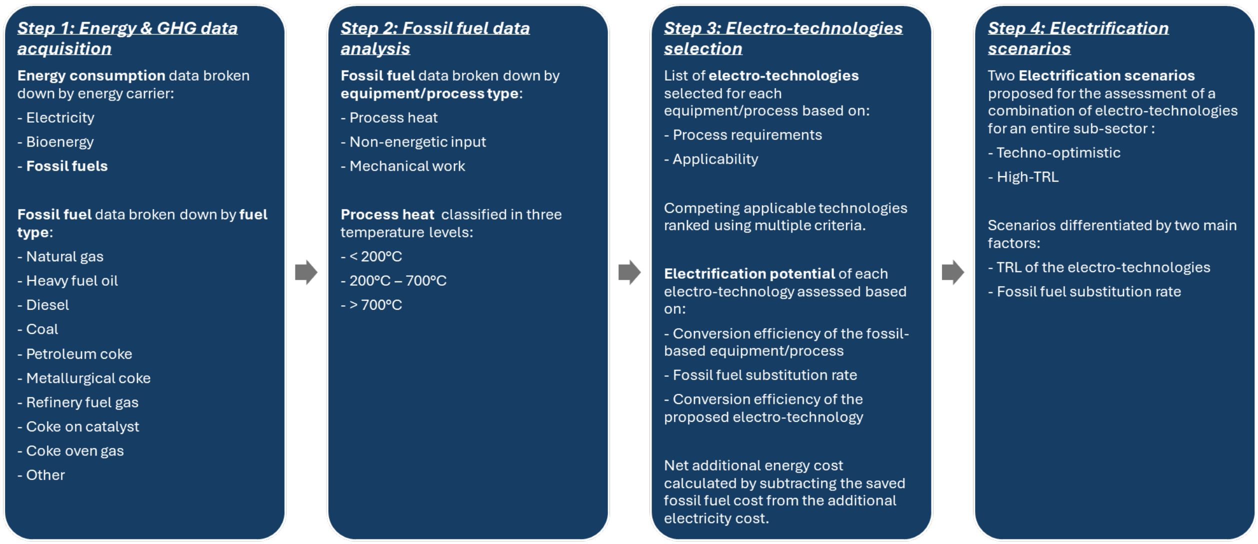

Figure 1. *Methodology*

2.1 Energy and GHG emissions inventories

Energy consumption and GHG emissions inventories for each industrial sub-sector are compiled from publicly available sources, such as annual reports from relevant agencies and organizations [1], [2], [8], [9], [10]. Energy consumption data are broken down by energy carrier, namely electricity, bioenergy, and fossil fuels. GHG emissions data are broken down by emission type, namely fossil emissions, process emissions, and biogenic emissions.

An additional step is to further break down the total fossil fuel consumption of each sub-sector into specific fuel types, such as diesel, natural gas and others.

2.2 Sub-process fossil fuel breakdown

The next step is to determine the breakdown of fossil fuel consumption by end-use category (e.g., industrial process heat, mechanical work, non-energy use) for each industrial sub-sector. To do this, each sub-sector is examined individually to identify its process steps and the distribution of fuels between these steps. The results of the analysis of fossil fuel breakdown for nine Canadian industrial sub-sectors are available on the Natural Resources Canada website [12]. A comprehensive data set was developed using a similar methodology for the thirteen targeted sub-sectors in Quebec, detailing their process steps and the amount and type of fuel consumed at each step. This data is used as the main input for the electrification potential calculations.

For industrial process heat applications, the applicability of the replacing electro-technologies depends heavily on the operating temperature [8]. Therefore, to enable a reliable assessment of electrification options, the use of fossil fuel for industrial process heat is divided into three temperature levels: low-temperature heat (<200 °C), medium-temperature heat (200–700 °C), and high-temperature heat (>700 °C), the two thresholds representing the maximum practical temperature of heat pumps and nichrome heating elements, respectively.

2.3 Electro-technologies

A set of electrical technologies (or electro-technologies) is evaluated, and the corresponding data on conversion efficiency and fossil-fuel substitution capability are compiled. Then, for each process or equipment, one or more suitable electro-technology options are identified qualitatively to replace fossil fuel-based ones based on the specific application and thermal compatibility. When multiple options are suitable, the final choice of technology is based on a logical multi-criteria approach, which gives primary importance to energy efficiency while considering factors such as reliability, ease of integration, maintenance needs, and technology maturity.

The resulting analysis reports the expected reductions in GHG emissions and fossil fuel consumption, as well as the additional electricity demand required to enable these substitutions. The additional annual electricity (ΔE_{el}) is formulated by Equation 1.

$$\Delta E_{el} = \frac{\eta_f}{\eta_e} \times \left(\sum_{i=1}^{N} E_{fuel,i} \times \sigma_i\right) \quad (1)$$

Where $E_{fuel,i}$ is the fossil fuel consumption before electrification, σ_i is the fossil fuel substitution rate, defined as the fraction of energy used by this fuel that is replaced by the electrified system. These variables are summed for each of the fuels used in the processes before electrification, from $i = 1\ to\ N$, where N is the total number of fossil fuels. The term η_f is the conversion efficiency of the fossil fuel equipment and η_e is the conversion efficiency of the electrical technology. These conversion efficiencies are defined as the energy transferred to a specified delivery point relative to the consumption of fossil fuels or electricity, respectively.

Based on energy prices in Quebec [13], the net additional energy cost is calculated for each electro-technology by deducting the savings on fossil fuel costs from the cost of the additional electricity demand, as formulated by Equation 2.

$$C_{add} = -\left(\sum_{i=1}^{N} E_{fuel,i} \times \sigma_i \times FC_i\right) + (\Delta E_{el} \times EC) \quad (2)$$

Where C_{add} is the annual net additional energy cost, FC_i is the unit fuel cost, and EC is the unit cost of electricity.

Using Equations 1 and 2, the electrification potential and net additional energy cost can be estimated at the process or equipment level. To assess the electrification potential of an entire industrial sub-sector, it is necessary to examine a portfolio of electro-technologies that, together, replace fossil fuel-consuming processes and equipment within that sub-sector. To this end, electrification scenarios combining several electro-technologies are proposed and examined in the following section.

2.4 Electrification scenarios

To assess the electrification potential of an industrial sub-sector, two scenarios are considered based on the technology readiness level and the technically feasible fossil fuel substitution rate associated with each electro-technology. The first includes only commercially mature, high technology readiness level (high-TRL) technologies, and relatively lower substitution rates for each process or equipment, to estimate a conservative (lower-bound) electrification potential, while the second incorporates emerging, low technology readiness level (techno-optimistic) technologies, and relatively higher substitution rates, to capture a more ambitious (upper-bound) potential.

In the techno-optimistic scenario, electro-technologies are always selected so that 100% substitution is achieved, or at least reasonably achievable under some future combination of similar-performance technologies [14], [15], [16], [17]. This includes the substitution of process gases that are inherent by-products of industrial operations, such as refinery fuel gas. This implies that alternative sustainable utilizations, beyond their current process-related uses, would be found in each case.

In the high-TRL scenario, substitution rates reflect the more conservative approach. This includes a 0% substitution rate for process gases across all end-use categories, reflecting the significant challenge of establishing those alternative sustainable utilizations without reemitting carbon. It also includes partial substitution rates for high-temperature process heat applications in cement, lime, and similar industries, where there is evidence that technically, partial electrification is significantly more straightforward than full substitution.

3. Results

3.1 Energy and GHG emissions inventories for Quebec's thirteen industrial sub-sectors in 2019

Figure 2 illustrates the aggregated data on energy consumption and GHG emissions for thirteen industrial sub-sectors in Quebec (2019), in accordance with the methodology. The combined production of wood pulp and primary aluminum dominates the energy landscape due to its already large consumption of electricity and biomass, while fossil fuel usage is more evenly split across sub-sectors.

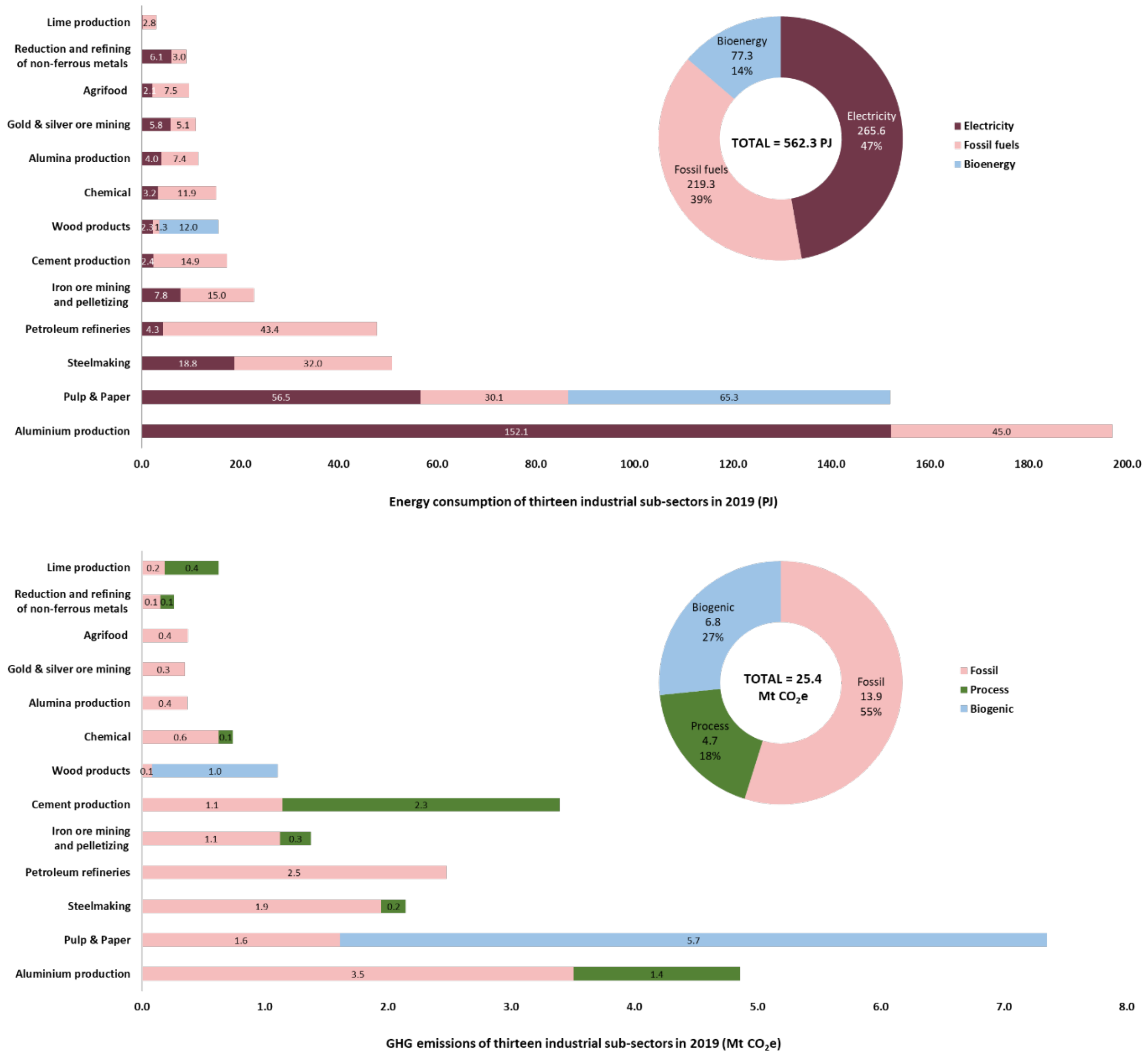

Figure 2. *Energy consumption and GHG emissions inventories of thirteen industrial sub-sectors in Quebec in 2019*

Figure 3 shows the breakdown of total fossil fuel consumption for each sub-sector by fuel type. Natural gas is the dominant fuel, followed by petroleum coke, which is used in large part as a feedstock to bake anodes for the aluminum sub-sector.

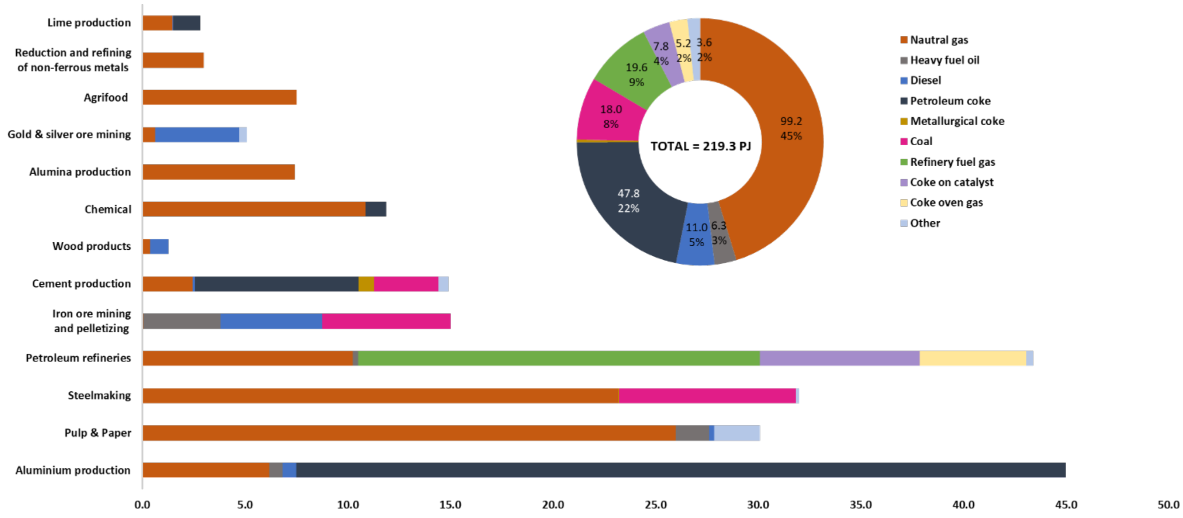

Figure 3. *Fossil fuel consumption (per fuel type) of thirteen industrial sub-sectors in Quebec in 2019 (PJ)*

3.2 Sub-process fossil fuel breakdown for thirteen industrial sub-sectors in Quebec in 2019

Figure 4 illustrates the distribution of fossil fuel consumption by end-use, in accordance with the methodology. Process heat is the dominant fossil fuel consumer for the studied thirteen sub-sectors, accounting for more than 62% of the total fossil fuel consumed by these sub-sectors.

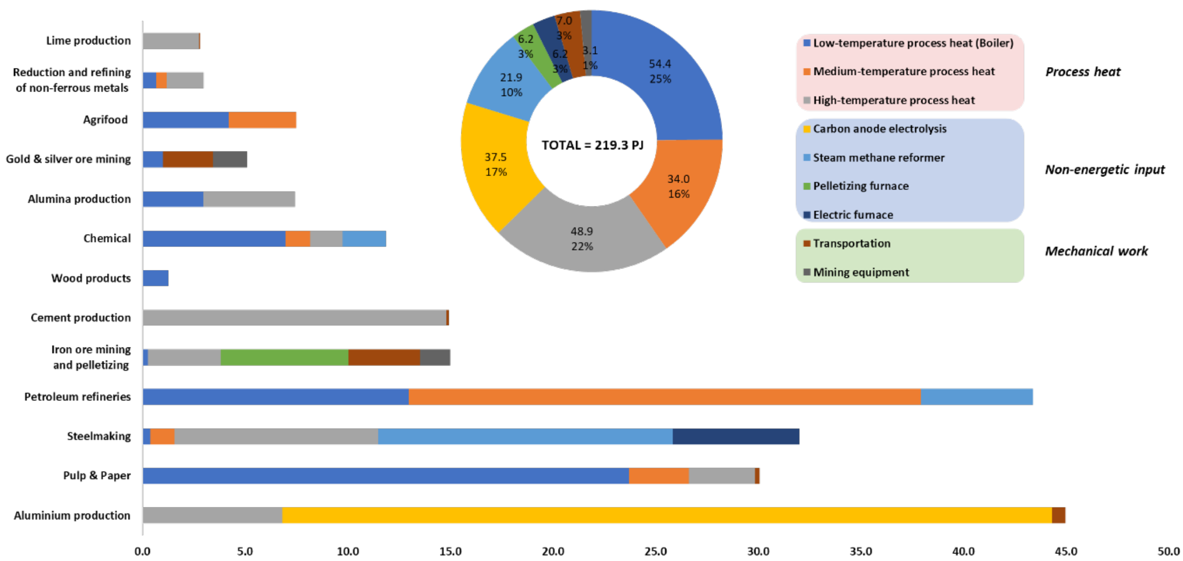

Figure 4. *Fossil fuel consumption (per end-user) of thirteen industrial sub-sectors in Quebec in 2019 (PJ)*

3.3 Electro-technologies selected for thirteen industrial sub-sectors in Quebec

Table 1 presents the list of technologies selected for the thirteen industrial sub-sectors studied, with their respective conversion efficiencies.

Table 1. *Identified electro-technologies for fossil-fuel processes and their characteristics*

End-use category	Fossil-consuming process or equipment	η_f	Electro-technologies	TRL	η_e	References
Process heat (< 200°C)	Conventional boiler	85%	High-temperature heat pump	High	133%	[18]
Process heat (200 – 700°C & > 700°C)	Process heating such as cement kiln	85%	Electric resistance heating	High	98%	[16]
Process heat (> 700°C)	Process heating such as cement kiln	85%	Plasma heating	Medium	75%	[19]
Process heat (> 700°C)	Carbon anode baking (in aluminum production)	85%	Inert anode preparation	Low	234%	[20]
Non-energetic input	Carbon anode electrolysis (in aluminum production)	100%	Inert anode electrolysis	Low	164%	[21] ,[20]
Non-energetic input	Steam methane reformer (For natural gas direct reduced iron or NG-DRI)	100%	Molten oxide electrolysis	Low	97%	[22]
Non-energetic input	Steam methane reformer (For natural gas direct reduced iron or NG-DRI)	100%	Water electrolysis for H_2 production (For hydrogen direct reduced iron or H_2-DRI)	Medium – High	60%	[23], [24]
Non-energetic input	Steam methane reformer	100%	Water electrolysis for H_2 production	High	70%	[25]
Mechanical work	Diesel truck	35%	Hybrid (battery + catenary) truck	High	83%	[26]
Mechanical work	Diesel train	35%	Hybrid (battery + catenary) train	High	86%	[27]
Mechanical work	Diesel drills (mining equipment)	35%	Electric drills	High	85%	[29] ,[28]

For most end-users utilizing process heat from fossil fuels, a uniform average conversion efficiency of 85% has been assumed, which corresponds to reasonably efficient industrial equipment [30]. It should be noted that this represents the efficiency of combustion at delivering heat, not the effectiveness of the process at using heat. The same delivery point then applies to the corresponding electro-technology, which preserves the validity of Equation 1 regardless of process-specific definitions of energy efficiency. One drawback of this method is that if the recovery of waste heat from combustion gases plays an irreplaceable role in the process energy efficiency, which is difficult to determine in the absence of detailed process knowledge, then Equation 1 will underestimate the electricity demand.

As shown in **Table 1**, a 100% conversion efficiency is assigned to non-energetic input end-use categories when estimating their electrification potential using Equation 1. This simplifying assumption treats the energy content of chemical inputs (e.g., natural gas used as a reducing agent or carbon in anodes) as fully contributing to the corresponding process requirement. The corresponding electro-technology is then assessed with respect to the same requirement. (This may lead to efficiencies above 100% on such basis, which would only imply that the process requires less cooling after electrification.)

For low-temperature process heat, heat pumps are identified as replacing all conventional boiler systems across the thirteen industrial sub-sectors considered in this study. For medium-temperature process heat, electric resistance heating is proposed as a substitute for conventional fossil-fuel-based furnaces in all studied sub-sectors. For high-temperature process heat, plasma heating is proposed for iron ore pelletizing furnaces. For all other high-temperature furnace applications, electric resistance heating is considered as the replacement technology. For the diesel-consuming equipment, the electro-technologies considered always include some combination of battery-driven and catenary-driven electric motors.

For the aluminum sub-sector (carbon anode preparation and electrolysis), projects involving inert anode preparation and electrolysis are treated as electro-technologies with artificially high effective efficiencies to maintain consistency with Equation 1. These efficiency values have no thermodynamic significance; they are used solely to calculate the additional electricity demand associated with the combined implementation of inert anodes [20].

Only two non-energetic input end-use categories, namely pelletizing furnaces in the iron ore mining and pelletizing sub-sector, and electric furnaces in the steelmaking sub-sector, are processes with some fossil fuel requirements that cannot be electrified, and therefore, no electro-technologies are assigned to those categories.

3.4 Electrification scenarios for thirteen industrial sub-sectors in Quebec

Table 2 presents the list of electro-technologies selected for the techno-optimistic scenario. This scenario models the potential for complete fuel substitution for all fuel types in all processes or equipment.

Table 2. *Electro-technologies in the techno-optimistic scenario*

Electro-technologies	Fossil-consuming process or equipment	Fossil fuel types	σ	Saved fossil fuel (PJ/yr)	Additional electricity (PJ/yr)
High-temperature heat pump	Conventional boiler	Natural gas Refinery fuel gas Heavy fuel oil Diesel	100%	49.7	31.7
Electric resistance heating	Medium- and high-temperature process heat	Natural gas Refinery fuel gas Heavy fuel oil Coal (or coal-derived gas) Petroleum coke Metallurgical coke Other	100%	60.4	52.4
Plasma heating	High-temperature process heat	Heavy fuel oil	100%	3.5	4.0
Inert anode preparation	Carbon anode baking	Natural gas Heavy fuel oil	100%	4.5	1.7
Inert anode electrolysis	Carbon anode electrolysis	Petroleum coke	100%	37.5	22.8
Molten oxide electrolysis	NG-DRI (steam methane reformer)	Natural gas	100%	14.4	14.8
Water electrolysis for H_2 production	Steam methane reformer	Natural gas Refinery fuel gas	100%	7.6	10.7
Hybrid (battery + catenary) truck	Diesel trucks	Diesel	100%	4.5	1.8
Hybrid (battery + catenary) train	Diesel trains	Diesel	100%	1.5	0.6
Electric drills	Diesel drills (mining equipment)	Diesel	100%	3.1	1.3

Figure 5 presents the techno-optimistic electrification scenario results. In this scenario, fossil fuel use in thirteen sub-sectors decreases by 85%, corresponding to a 51% reduction in associated GHG emissions. To achieve these reductions, annual electricity demand increases by 53% (about 39 TWh), resulting in an estimated additional annual energy cost of approximately C$656 million.

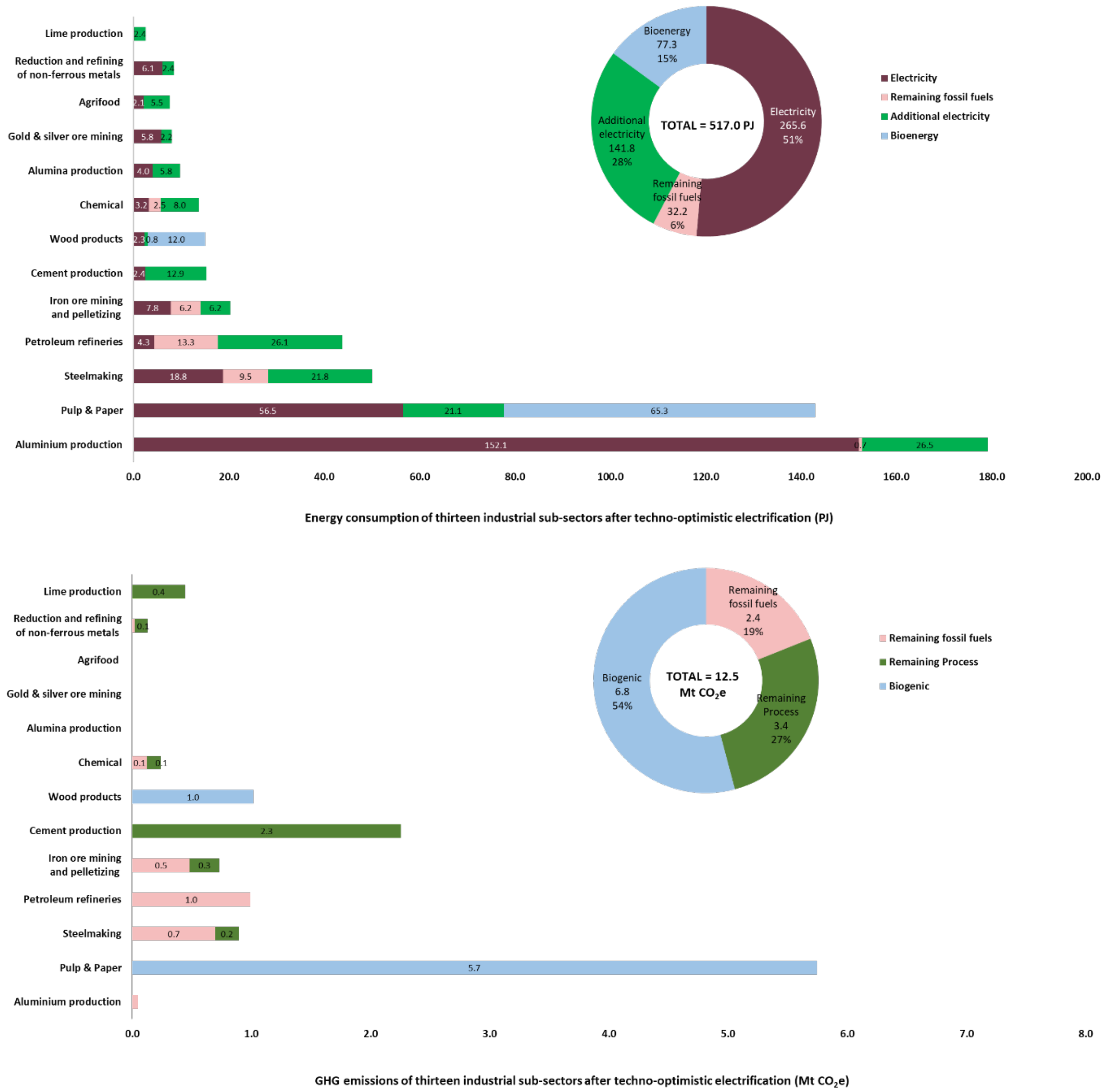

Figure 5. *Energy consumption and GHG emissions of thirteen sub-sectors after techno-optimistic electrification*

Table 3 presents the list of electro-technologies selected for the high-TRL scenario. For the H_2-DRI process in the steelmaking sub-sector, a 30% substitution is considered due to the process constraints and infrastructure compatibility [23], [24]. For iron ore pelletizing, the furnace air can be preheated significantly using electricity, and only this application is considered high-TRL, resulting in a substitution rate of 30% for heavy fuel oil and 0% for coal [19]. For high-temperature process heat applications in cement, lime, and similar industries, a conservative fuel substitution rate of 30% is selected, reflecting partial electrification of the primary combustion heat sources without full process redesign. This value is used as a structured scenario assumption in the absence of standardized substitution factors in the literature, and it could later be subject to a sensitivity analysis.

Table 3. *Electro-technologies in the high-TRL scenario*

Electro-technologies	Fossil-consuming process or equipment	Fossil fuel types	σ	Saved fossil fuel (PJ/yr)	Additional electricity (PJ/yr)
High-temperature heat pump	Conventional boilers	Natural gas Heavy fuel oil Diesel	100%	41.2	26.0
Electric resistance heating (partial substitution)	High-temperature process heat (In cement, lime and Iron ore pelletizing sub-sectors)	Natural gas Heavy fuel oil Coal (cement) Petroleum coke Metallurgical coke Other	30%	6.4	5.5
Electric resistance heating (full substitution)	Medium- and high-temperature process heat	Natural gas Heavy fuel oil Other	100%	30.6	26.6
Water electrolysis for H_2 production for H_2-DRI	Steam methane reformer for NG-DRI	Natural gas	30%	4.3	7.3
Water electrolysis for H_2 production	Steam methane reformer	Natural gas	100%	4.0	5.6
Hybrid (battery + catenary) truck	Diesel trucks	Diesel	100%	4.5	1.8
Hybrid (battery + catenary) train	Diesel trains	Diesel	100%	1.5	0.6
Electric drills	Diesel drills (mining equipment)	Diesel	100%	3.1	1.3

Figure 6 presents the high-TRL electrification scenario results. In this scenario, fossil fuel use in thirteen sub-sectors decreases by 44%, corresponding to a 21% reduction in associated GHG emissions. To achieve these reductions, annual electricity demand for these sub-sectors must be increased by 28% (about 21 TWh), resulting in an estimated additional annual energy cost of approximately C$254 million.

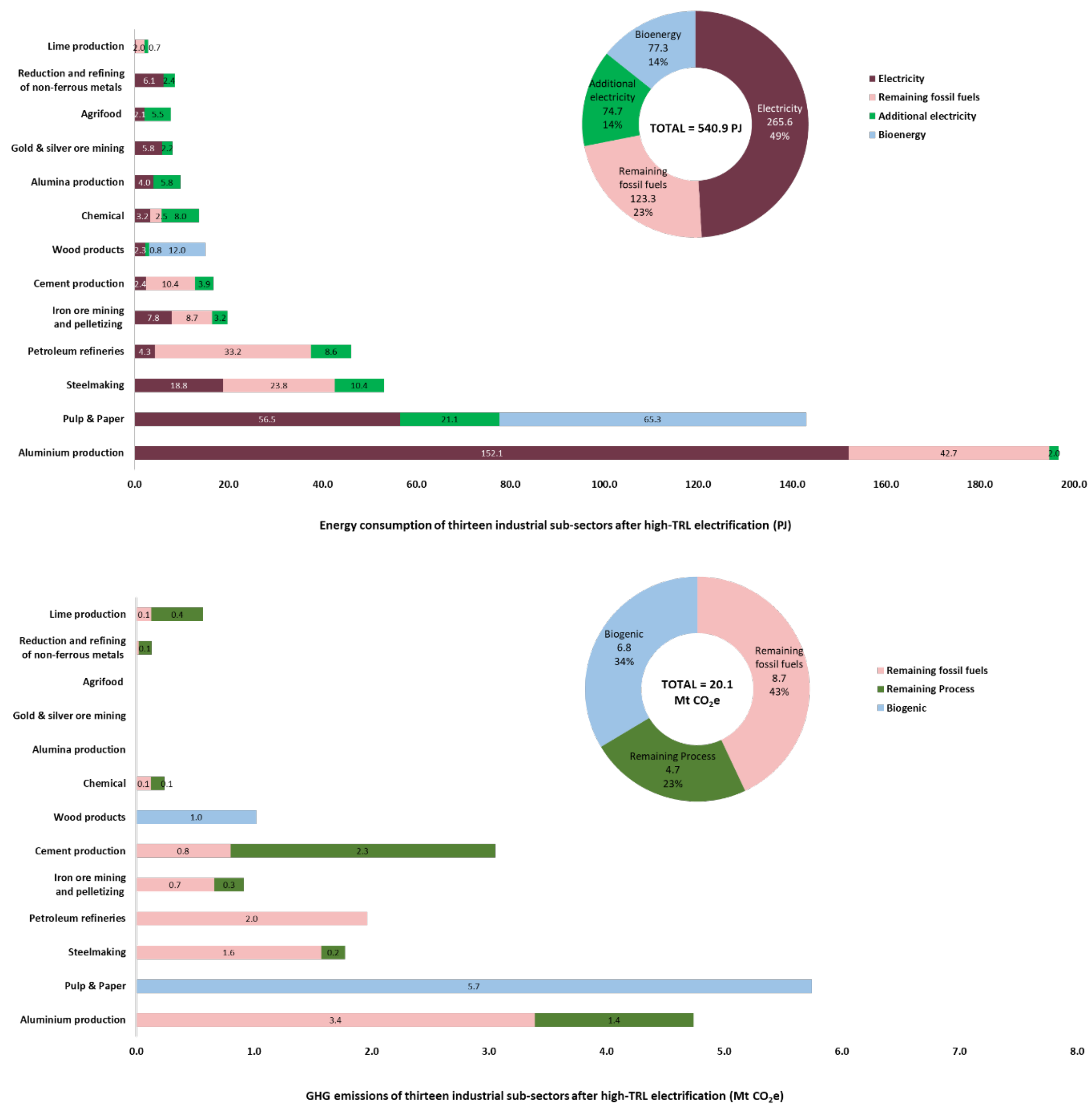

***Figure 6**. Energy consumption and GHG emissions of thirteen sub-sectors after high-TRL electrification*

Figure 7 shows the types and combinations of electro-technologies selected for the thirteen industrial sub-sectors under the two electrification scenarios. In both scenarios, resistance heating accounts for the largest increase in annual electricity demand, as it replaces medium- and high-temperature industrial process heat from fossil fuels. These heating needs collectively represent the largest consumption of fossil fuels among the thirteen sub-sectors, as shown in **Figure 4**.

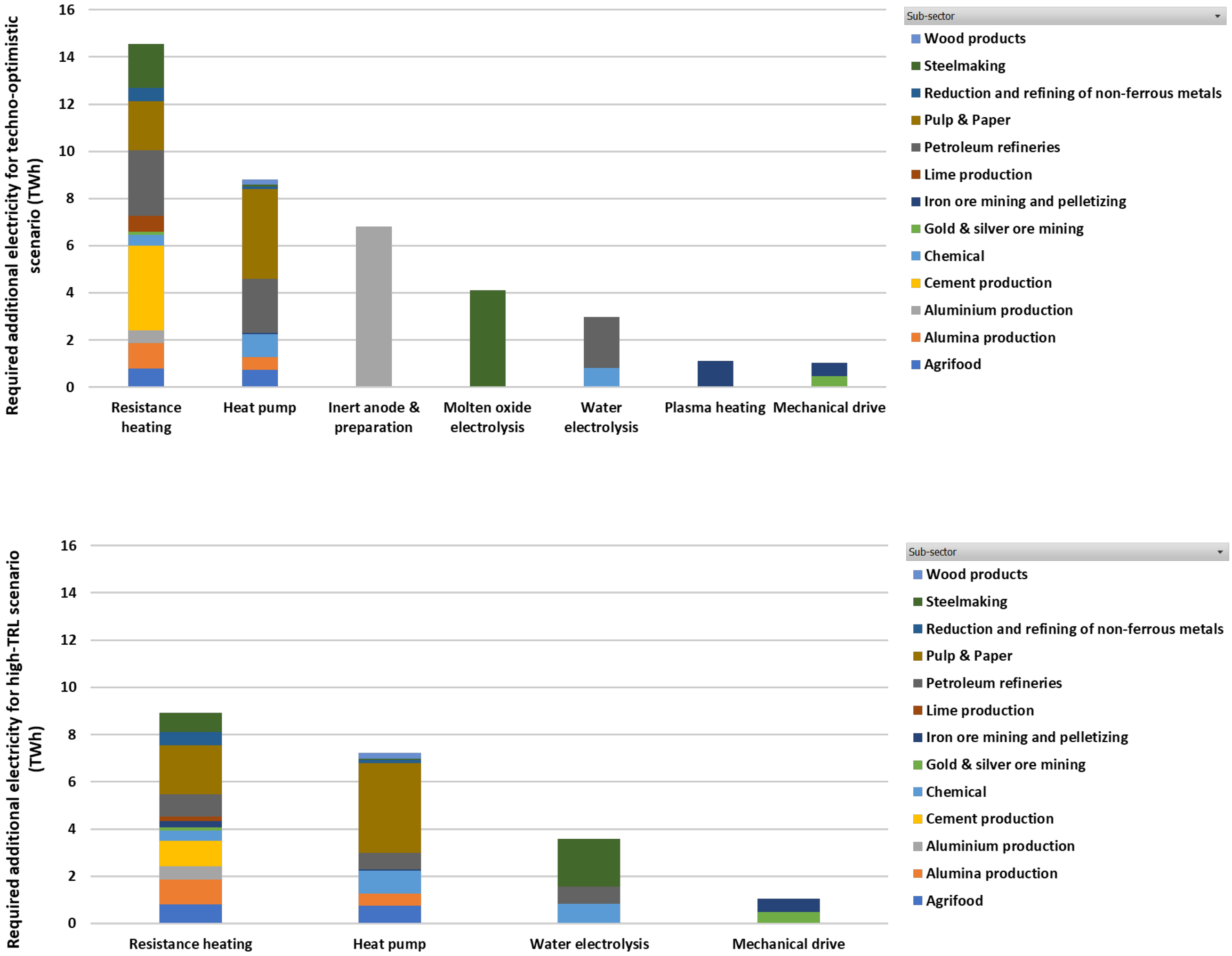

Figure 7. *Additional electricity demand for techno-optimistic scenario (above) and high-TRL scenario (below) in TWh*

4. Discussion

The previous section presented the theoretical potential for electrification of thirteen industrial sub-sectors in Quebec, based on fossil fuel consumption in 2019. Many factors will limit the integration of these electro-technologies in industry in practice:

- Some electro-technologies, such as resistance heating, present integration challenges specific to each sub-sector. Even if the technology is simple, the engineering and implementation can be complex. It should be noted that highly integrated facilities such as oil refineries and chemical plants rely extensively on heat recovery. Electrification significantly alters the process heat balance (i.e., composite curves), requiring careful thermal and operation redesign due to the dynamics of electrical versus thermal systems.
- The electrification of the steel and oil refinery sub-sectors, as illustrated in the techno-optimist scenario results, implies that new uses will be found for by-product gases. Until such uses are identified and technically feasible, it may be more realistic to limit the expected electrification of these sub-sectors to the smaller amount sufficient to eliminate discretionary fuel purchases, in line with the high-TRL scenario.

- In some cases, the long intervals between industrial equipment replacement cycles, combined with company-specific dynamics, create circumstantial opportunities for electrification at certain sites rather than others. It is therefore difficult to predict on what time horizon any specific electrification scenario can be realistic or not.
- The electrification of heavy industry will require flexible management of new electrical loads that effectively replace fossil fuels. This applies primarily to grids with a high proportion of intermittent renewable energy. Energy management solutions such as demand response are critical to reducing peak demand, managing renewable energy intermittency, and avoiding grid overload. This flexibility can also limit the need for grid capacity expansion, enabling a more resource-efficient transition to a decarbonized industrial sector. In Quebec specifically, where most renewable energy is not intermittent, process flexibility to interrupt for up to four hours is nevertheless highly valued for managing winter peaks. However, most heavy industrial processes are continuous and rigid in their operation. Depending on the configuration of the modernized equipment, flexibility after electrification will likely be more limited for direct-fired applications than for indirect-fired applications, which benefit from the parallelization of multiple boilers and the possibility of heat storage.

Comprehensive scenario planning for industrial decarbonization requires arbitrating between different decarbonization measures, which is beyond the scope of this work, and requires considering several aspects, including the following key elements:

- The availability of biomass as an alternative could encourage companies to forego electrification where bioenergy offers greater comparative advantages, such as currently low prices per kilowatt-hour, minimal fuel upgrading requirements in some cases such as cement kilns, and the possibility of combining it with carbon capture and storage (BECCS) for negative emissions.
- CCS appears inevitable for the deep decarbonization of industrial sub-sectors that generate process CO_2, notably cement & lime production. This expected reliance on CCS paves the way for the deployment of BECCS in these sectors, which could reduce the role of electrification as well as more energy-intensive negative emissions technologies such as direct air capture. Given Quebec's relatively abundant biomass resources, particularly forest residues, such an approach could be particularly advantageous. As a result, some Quebec industries could delay their investments in electrification, anticipating that BECCS could offer a more economically attractive path, combining the avoidance of electricity cost increases with the potential revenues from negative emissions.
- However, for most industrial sub-sectors, which generate no process CO_2, electrification remains a realistic, low-regret pathway to full decarbonization, especially after first reducing their energy usage through process-level energy efficiency measures (not considered in this work).

5. Conclusion

This article examines the potential of electrification to decarbonize thirteen industrial sub-sectors in the province of Quebec, which account for approximately 70% of Quebec's industrial emissions and an even larger share of those considered heavy industrial. It focuses on mapping fossil fuel consumption by equipment category, on estimating the suitability of electrotechnologies for each category, and on estimating the corresponding energy efficiency gain after electrification. It finds that most fossil fuel consumption in most sub-sectors can be replaced by electricity, significantly reducing GHG emissions, even in a scenario limited to technologies with high-TRL and conservative substitution rates. The increase in annual electricity consumption ranges from 21 to 39 TWh between scenarios, representing approximately 10 to 20% of the province's current electricity consumption.

However, even under the most optimistic scenario, a significant portion of GHG emissions remains, primarily due to CO_2-generating process chemistry. Thus, comprehensively decarbonizing Quebec's industry would require some reliance on pathways other than electrification, which in turn would reduce the electrification achieved in practice.

Data availability statement

All relevant parameters are indicated in the document. As described in the methodology section, to assess the potential for electrification, it was necessary to determine fossil fuel consumption by process or by equipment. This was made possible by compiling a high-level energy and emissions inventory for Quebec from publicly available sources, such as annual reports from relevant agencies and organizations, including the Office of Energy Efficiency (OEE), the Canada Energy Regulator (CER), Environment and Climate Change Canada (ECCC), the National Inventory Report (NIR) and the Canadian Energy and Emissions Data Center (CEEDC).

Author contributions

According to the CRediT guidelines below are the contributions of each author-

Soseh Zadoorian: Process engineer, project member, Conceptualization – Data Curation – Formal Analysis – Methodology – Software – Validation – Visualization – Writing - original draft

Omar Mostafa: Junior research officer, project member, Conceptualization – Validation – Software – Writing - Review & Editing

Etienne Bernier: Senior scientific advisor, project member, Supervision – Writing - Review & Editing

Abdelaziz Hammache: Research scientist, project member, Conceptualization – Data Curation – Methodology – Software – Review & Editing

Competing interests

The authors declare that they have no competing interests.

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