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Review

Renewable Energy and Decarbonization in the Canadian Mining Industry: Opportunities and Challenges

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Abstract: Mining in Canada stands as one of the most energy-intensive sectors, playing a pivotal role as a significant provider of copper, nickel, and cobalt to the international market. Anticipated growth in the global population, coupled with the transition of several low-income economies to middle-income status, is poised to escalate the demand for essential raw materials. This surge in demand is expected to drive an increase in energy consumption across various stages of the Canadian mining industry, encompassing exploration, extraction, processing, and refining. Due to their geographical constraints, most Canadian mining operations rely heavily on fossil fuels such as diesel and heavy fuel. Considering the global shift towards decarbonization and the pursuit of net-zero emission targets, exploring avenues for adopting electrification solutions and integrating renewable energy technologies, particularly in sizable surface mines, is imperative. Within this context, our study delves into the challenges and prospects associated with infusing renewable energy technologies and embracing electrification alternatives within Canadian mining practices. This exploration encompasses a comprehensive review of pertinent literature comprising academic research, technical analyses, and data disseminated by international entities and experts. The findings underscore a prevalent trend wherein Canadian mining enterprises are prominently investing in robust electric truck fleets, particularly for heavy-duty operations. Additionally, incorporating renewable energy solutions is notably prevalent in remote sites with extended operational lifespans. However, an in-depth examination reveals that the most formidable hurdles encompass successfully integrating renewable energy sources and battery electric vehicles. Financial constraints, logistical intricacies, and the imperative to enhance research and development competencies emerge as pivotal challenges that demand strategic addressing.

Keywords: Canadian mining; mining decarbonization; mining electrification; future mining; renewable energy; clean-energy technologies

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1. Introduction

The mining industry, which includes a wide range of activities like such as exploration and extraction, as well as processing, sophisticated manufacturing, and recycling, is crucial to Canada. For a variety of Canadian industries, including manufacturing, transportation, construction, and energy, it is a crucial supply of the necessary materials. [1–3]. Nevertheless, akin to global trends in mining, the Canadian mining industry stands out for its substantial energy consumption. Notably, as indicated by the Canadian greenhouse gas (GHG) inventory, the industry's GHG emissions surged from 4.3 million metric tons of CO_2 equivalent to 6.4 million metric tons between 2015 and 2019. This upward trajectory is predicted to persist until 2035, driven by the escalating demand for raw materials and the establishment of new mining sites in remote areas devoid of access to the public power grid [4]. Energy consumption in the Canadian mining sector can be broadly categorized into two main groups: off-grid and grid-connected operations. In on-site power generation and transportation, off-grid mining activities primarily hinge on diesel fuel usage [5–7]. On the other hand, grid-connected mining endeavors exhibit a certain reliance on fossil fuels, particularly in transporting extracted minerals. Nevertheless, these mining operations remain highly sensitive to fluctuations in fossil fuel prices, given that a considerable portion of their expenses is directed towards energy production, a significant fraction of which originates from fossil fuels.

A forecast indicates that by 2035, the energy demand for mining operations is poised to surge by as much as 36% [8]. While acknowledging the significant risks climate change poses to the mining sector, the Mining Association of Canada (MAC) has predominantly focused on preventative measures rather than building resilience. A prevailing strategy embraced by Canadian mining companies in addressing climate change involves the reduction in greenhouse gas (GHG) emissions and the enhancement of energy efficiency. This orientation is evident in various trade journal articles, encompassing topics such as emission caps and legislative frameworks concerning carbon emissions [9], company-specific initiatives aimed at emission reduction [10], adoption of GHG reduction strategies based on the Kyoto Protocol [11], utilization of carbon emission trading schemes and offsetting [12], deployment of technologies for emission mitigation [13], and the exploration of carbon capture and storage technologies.

Due to Canada's action on climate change, Canadian mining companies might encounter heightened short-term financial risks. Adopting strategies such as carbon pricing, which involves taxing greenhouse gas (GHG) emissions, is gaining traction [14–16]. However, this taxation based on emissions can lead to cost inflation in mining activities for specific mining operations characterized by high energy and fuel consumption levels. Simultaneously, the cost of securing financial resources is expected to rise as shareholders and investors amplify their concerns about climate-related issues. Mining corporations are experiencing growing pressure from pension funds, institutional investors, and the environmental, social, and governance (ESG) investment community to demonstrate and implement their commitments to adopting low-carbon technologies [17]. Some investors have even indicated plans to delay investments in specific companies or entirely divest from such entities if there is no observable progress.

In response to these multifaceted risks, the Canadian mining sector must shift towards more sustainable practices [18]. This would showcase responsible behavior and serves as a risk-mitigation strategy that benefits investors and businesses. This shift involves investing in eco-friendly processing techniques that mitigate water-related risks and intensifying efforts to reduce the industry's carbon footprint. Investments in low-carbon technologies, particularly within renewable energy, battery storage, and electric vehicles, have significantly expanded.

Hence, the focus of this study is to document the recent endeavors undertaken by the Canadian mining industry to adopt and implement clean technologies such as photovoltaic (PV) solar plants, wind turbines, and geothermal energy. These efforts aim to achieve net-zero scope 1 and 2 GHG emissions by 2050 or sooner, aligned with the objectives of the Paris Agreement. Additionally, the study introduces existing electrification alternatives within Canadian mining operations, highlighting both opportunities and challenges. However, this literature review excludes oil and gas operations. It focuses only on mining operations associated with metallurgical processes.

The remainder of this paper is organized as follows: Section 2 outlines the research methodology. Current ongoing renewable energy (RE) development projects in Canadian mining are presented in Section 3. In Section 4, opportunities for integrating RE into mining operations are discussed. Section 5 provides an overview of electrification alternatives in Canadian mines. Section 6 delves into the challenges associated with RE integration and transport electrification in Canadian mines, while Section 7 concludes the paper with a summary and recommendations.

2. Research Methodology

Peer-reviewed papers were found by conducting queries across major bibliographic databases such as Scopus, Web of Science, Google Scholar, and Compendex through pertinent keywords, such as “Canadian mining”, “mining decarbonization”, “mining electrification”, “future mining”, “energy consumption in mining”, and “clean-energy technologies”. In some cases, the list of peer-reviewed articles also contained pertinent information from conference proceedings. The list of references for investigation also contained a few technical publications from the Canadian government, magazine journals, and national news. For the comprehensive assessment of renewable energy and decarbonization in the Canadian mining industry, the authors read over 196 papers, mostly journal articles. After the general review, they studied 111 articles in more depth to address the study goals. This assessment’s concepts and findings are mostly based on an in-depth examination of these 100 publications. Twenty-four of these specifically address how operator’s actions affect fuel energy use and greenhouse gases or loading and hauling operations efficiency by integrating clean technologies and storage systems.

The review largely deals with studies conducted in the recent decade. For instance, only four of the detailed reviews of 111 articles are older, two from 2011 and the others from 2012. There are two factors at play here. First, to establish the field’s current state, the authors planned to concentrate on the most recent findings. Second, the mining industry has been under pressure to be more efficient due to worries about sustainability, namely the effect of climate change, which has led to increased research efforts over the past ten years. Figure 1 illustrates the methodology used in this investigation.

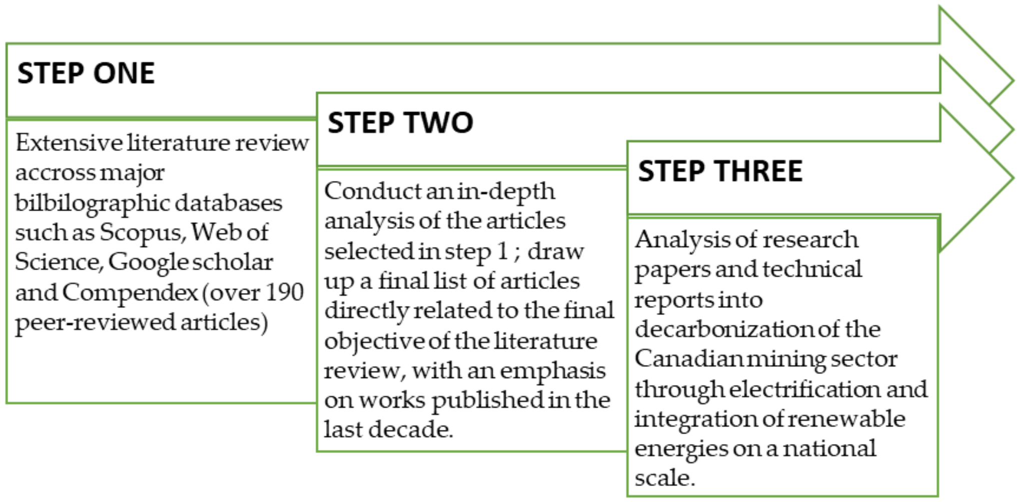

Figure 1. The methodology used in this investigation.

3. Current Active Projects Related to Renewable Energy Development in Canadian Mining

The Research Centre for Energy Resources and Consumption foresees a significant surge in primary energy demand for the global Canadian mining industry over the next decade, specifically in the extraction of copper ores for the renewable energy sector, rare earth for the semiconductor industry, and lithium and nickel ores for the manufacture of electric car batteries. This demand is projected to escalate from 8% of primary energy consumption to 15–20% by 2035 [19]. This growth prompts the expectation that Canadian renewable energy technologies, the semiconductor industry, and electric vehicle and battery developers will play a pivotal role in delivering adaptable, proven, and low-carbon energy solutions to meet the escalating energy requirements of the mining sector [20]. However, in this context, it is crucial to assess the potential environmental impact of these mining operations.

In essence, Canadian mining operations have the potential to reduce their energy consumption and greenhouse gas emissions based on diesel fuel consumption through the implementation of energy recovery systems (ERS) [21], integration of renewable energy (RE) sources [22], transport electrification, and adoption of carbon capture (CC) technologies [23]. Additionally, Canadian mines are positioning themselves to cut expenses by curbing diesel usage and carbon emissions, especially as Canada is a pioneer as the first significant mining jurisdiction to enforce a national carbon pricing strategy [24]. Addressing the energy-related challenges in the mining industry will necessitate a blend of renewable energy solutions and electrification. To facilitate this, the Canadian government has committed CAD 2.3 billion to establish a research and development (R&D) framework, propelling Canada into a leadership role in renewable energy solutions. This framework includes targeted funding initiatives to bolster renewable energy within the mining sector [25].

Despite the harsh winter conditions in Canada's northern regions, integrating renewable energy sources has demonstrated compelling cost savings at remote sites. The Raglan Mine project, undertaken by Glencore, stands out as a notable example. This pioneering initiative, led by TUGLIQ Energy, features the world's first wind project incorporating various energy storage technologies. The project integrates two wind turbines with a total capacity of 6 MW (Figure 2) alongside diverse storage systems such as hydrogen fuel cells, lithium-ion batteries, and a flywheel [26]. These two turbines contribute approximately 10% of the mine's electricity demand, resulting in savings exceeding 4 million liters of diesel annually and a reduction of 12,000 tonnes in emissions such as carbon dioxide (CO_2), nitrogen oxide (NO_X), hydrocarbon (HC), and particulate matter (PM). By incorporating two additional wind turbines, the mine's renewable energy capacity would scale to 12 MW, its energy storage capacity would increase to 6 MW/2 MWh, and its yearly diesel consumption would plummet by 6.6 million liters [27].

In addition to the Raglan wind-storage hybrid project, Rio Tinto's Diavik Diamond Mine in Canada's Northwest Territories has operated with four 2.3 MW wind turbines since 2012. These turbines collectively comprise a wind farm with a demonstrated capacity of 9.2 MW and an annual production of 17 GWh. This setup provides an average of 10% of the mine's power needs and contributes to a reduction of up to 6% in GHG emissions [28].

Figure 2. Wind turbines at Raglan were installed in 2014 and 2018 [29].

Similarly, TMAC Resources, acquired by Agnico Eagle in 2021, embarked on an evaluation of wind and storage solutions for its Nunavut mine from 2016 to 2018. The aim of collaborating with Canadian independent power producer TUGLIQ Energy was to cut costs, decrease diesel consumption, and achieve environmental objectives. Analysis indicated that the chosen location possessed adequate wind resources for cost-effective power generation. The recommendation entailed a hybrid project with wind capacity ranging from 2 to 4.7 MW. Large Li-Ion batteries and a demonstration element for compressed air storage are integral to the energy storage system. This integrated setup is anticipated to curtail the mine's diesel consumption by 3.7 million liters annually.

Conversely, photovoltaic (PV) solar panels have found promising applications in electrifying isolated Canadian mine sites. A few notable projects include:

- PV System at Raglan Mine (Quebec): Commencing in July 2021, this study evaluates the efficacy of solar energy production in Canada's northern regions. The installation, located near the wind turbines at Mine 2, incorporates 108 bifacial panels, generating 40 kilowatt-peak (kWp) energy [30]. This project is still considered a pilot project in the northern region of Quebec.
- PV System at SunMine (British Columbia): Initiated in 2014, SunMine is a groundbreaking 2 MW solar field connected to the British Columbia grid. Remarkably, it is the first solar farm on a reclaimed abandoned mine site. Teck Resources invested CAD 70 million over five years to reclaim the site following the mine closure. The site continues to manage drainage water, as shown in Figure 3 [31,32].
- PV System at Snowline Gold's Forks Camp (Canada): An off-grid system at this remote gold mine encampment encompasses a lithium-ion battery bank, a power rack for equipment organization, and 64 bifacial modules on a ground mount (all rated at 27 kW). This configuration is expected to reduce carbon emissions by 90% and save an estimated 12,527 L of fuel annually by providing power to the 45-person exploration camp and recharging the battery bank [33].

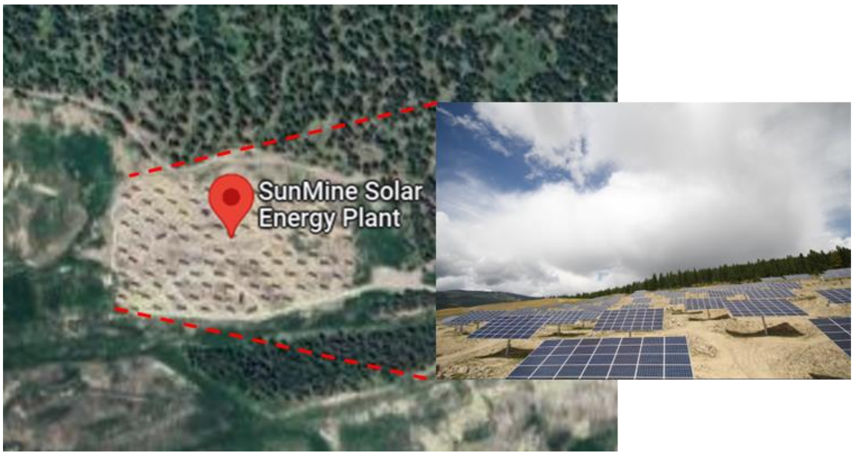

Figure 3. Aerial view of the SunMine solar energy plant in BC, Canada [31].

However, forthcoming Canadian mining ventures are embracing the integration of renewable energies in their new exploration sites. By 2025, Sabina Gold & Silver Corp. (now B2Gold) has outlined plans to incorporate renewable energy to power a segment of the Goose gold mine [34]. The company has proposed the installation of up to 13 wind turbines, collectively generating 4.5 MW of power, as per their submission to the Nunavut Impact Review Board. They also envision a 5 MW solar panel setup with 50 MWh of battery storage. In a similar vein, the Newmont-Goldcorp Éléonore mine, an active mining operation located in the Eeyou Istchee territory of James Bay in northern Quebec, took a significant step in 2020. In collaboration with researchers from the Institut National de la Recherche Scientifique of Montreal (INRS), the Hydro-Quebec research institute, and the engineering firm Hatch, the mine conducted a study to determine the potential of extracting geothermal energy from its dewatering water. Spanning three years, the study outcomes unveiled an impressive energy saving of approximately 39% on an annual propane bill amounting to CAD 2.5 million, coupled with a one-third reduction in GHG emissions [35].

Various ongoing mining projects [27–38] are actively evaluating the feasibility of integrating renewable energy, as shown in Table 1. While the progress varies across these projects, Canadian companies are firmly committed to transitioning toward sustainable energy sources. This shift is driven by the imperatives of curbing the impacts of climate change and embracing a greener, low-carbon economy.

Table 1. A list of some Canadian off-grid mining companies that have integrated or are in the process of integrating RE at their sites [27–38].

Project	Operator/Owner	Location	Type of RE
Port Hope Simpson	Search Minerals Inc.	New Labrador	Biofuels and/or hydroelectric
Raglan Mine	Glencore	Quebec	Wind energy, solar energy, and storage system
Zeus (Kipawa)	Matamec Explorations Inc.	Quebec	Hydroelectric (downstream)
Ashram	Commerce Resources Corp.	Quebec	Possibility of wind energy
Diavik Diamond	Rio Tinto	Northwest Territories	Wind energy
Hope Bay	Agnico Eagle	Nunavut	Wind energy, with a storage system
Goose Gold mine	B2Gold	Nunavut	Wind energy, solar energy, and storage system
Éléonore	Goldcorp	Quebec	Geothermal energy
Cynthia	Snowline Gold Corp.	Yukon	Solar energy

4. Opportunities for Integrating RE into Off-Grid Mining Operations

One of the foremost challenges in achieving sustainable development goals within off-grid mining operations stems from the pivotal shift from fossil fuel combustion to cleaner energy sources. Over the past decade, energy generation has witnessed remarkable technological advancements and cost reductions, particularly in wind and solar photovoltaic (PV) generation, thanks to widespread deployment. Recent insights into energy storage and renewable generation advancements suggest that the affordability of green energy is on the rise, attributed to climbing fossil fuel costs, the enforcement of climate change tax policies, and diminishing capital costs of eco-friendly generation and energy storage technology [39–41].

In Canada, the synergy of solar and wind resources presents an attractive solution for electrification and energy storage in remote areas. Notably, Canada's prime wind resource lies predominantly in the northern regions, where many off-grid mines are located. The solar and wind source maps for Canada, as depicted in Figure 4 [42–44], underscore this distribution. Among the provinces, the prairie provinces emerge as solar energy production hotspots: Saskatchewan leads with 1330 kWh of energy per kW per year, followed by Alberta with 1276 kWh/kW/yr, and Manitoba with 1272 kWh/kW/yr. Comparatively, remote sites in Nunavut can generate around 1092 kWh/kW/yr, Quebec around 1183 kWh/kW/yr, and Ontario around 1166 kWh/kW/yr. Notably, remote sites in Newfoundland and Labrador (NF.L.) and the Yukon present challenges for solar energy production due to factors such as high annual cloud cover in NF.L. and a combination of high latitude and cloudy weather in the Yukon.

Conversely, Canada's wind resources showcase considerable promise in its northern regions, aligning with the prevalent locations of remote off-grid sites. Wind speeds in these regions range from 6 m/s to 8 m/s and, in some cases, surge up to 10 m/s at an 80 m hub height. The abundance of such favorable wind resources lays a solid foundation for integrating renewable energies into Canadian mining operations. This endeavor presents businesses with a twofold opportunity: to decarbonize their operations and augment profit margins while mitigating the risks linked to the volatility of fossil fuel prices.

Furthermore, adopting clean energy brings forth an array of additional benefits. It can contribute to regional economic growth, bolster an organization's social license to operate by minimizing local noise and air pollution, foster mutually advantageous relationships, establish a competitive edge with environmentally conscious clients and investors within the environmental, social, and governance (ESG) realm, and even enable the establishment of renewable energy projects on repurposed mine sites. Such projects generate land leasing fees and contribute to community support after the mine's closure.

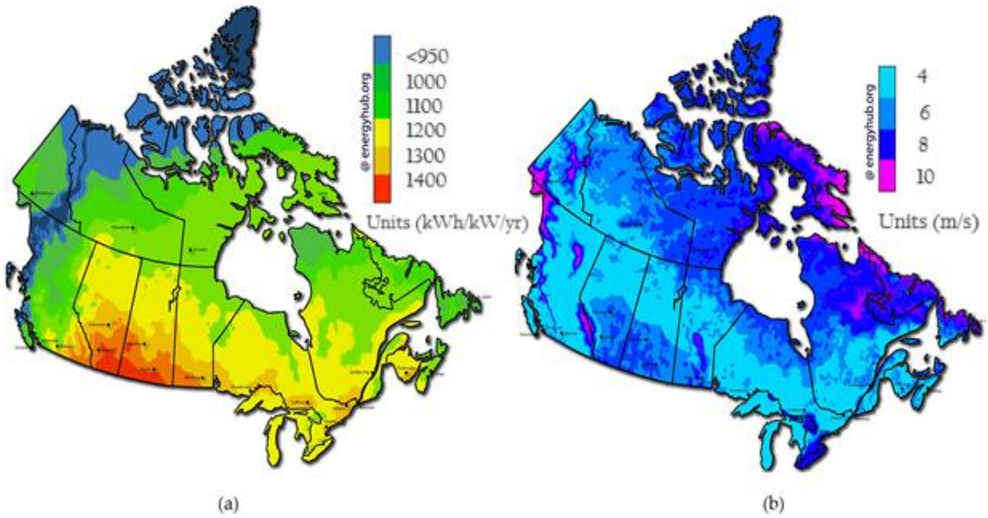

Figure 4. (**a**) Canadian solar source map; (**b**) Canadian wind source map [42–44].

4.1. Meeting Electricity and Heating through RE

An illustrative portrayal of Canadian mining practices and the types of fuel they utilize is presented in Table 2. Diesel fuel finds extensive application across many primary metal and non-metallic mineral manufacturing processes in Canada. Generally, the energy demand for non-metallic mineral production tends to be lower compared to that for metals [45]. Predominantly, this energy is channeled into heating processes, with a noteworthy proportion sourced from diesel fuel.

Table 2. An illustration of Canadian mining operations and related fuel sources.

Mining Process	Equipment and Activities	Fuel Type
Exploring, extracting, and operating	Power supply	Diesel
	Ventilation	Electricity
	Drilling	Diesel, compressed air, and electricity
	Pumping	Electricity
	Digging	Electricity and diesel
Material handling	Various transport systems (trucks, bulldozers, bulk trucks, etc.)	Diesel, electricity
	Continuous handling systems (conveyor, pumps, etc.)	Electricity
Processing	Comminution	Electricity
	Separation	Electricity and diesel
	Drying, firing, and smelting	Diesel

Process heat demand in the mining sector represents a substantial energy consumption factor. This demand spans a spectrum of temperatures, ranging from low to high. In an industrial context, low temperatures refer to those below 150 °C, medium temperatures range from 150 °C to 400 °C, and high temperatures exceed 400 °C [46]. The choice of technology at a mine site hinges on the fluctuating process heat requisites. For example, the conversion of iron oxide to metallic iron occurs within the temperature span of 800 °C to 1200 °C during steel production. In the copper smelting process, roasting copper ore into copper oxide necessitates a heat source operating from 250 °C to 350 °C. Similarly, the aluminum processing cycle involves elevating aluminum billets to soft solids at temperatures between 400 °C and 500 °C [47].

Commonly, steam is employed to generate low- to medium-temperature heat, while high-temperature heat is generated through direct heat sources, often via the combustion of fossil fuels. Presently, fossil fuels predominantly cater to high-temperature heat demands in mining operations. Figure 5 underscores that most available renewable energy (RE) technologies on the market primarily cater to low- or medium-temperature process heat requirements, rendering them suitable for specific applications. However, for high-temperature heat production beyond 550 °C, wind- and solar-based solutions remain in the research and demonstration phase at experimental sites, and their commercial implementation is yet to be realized.

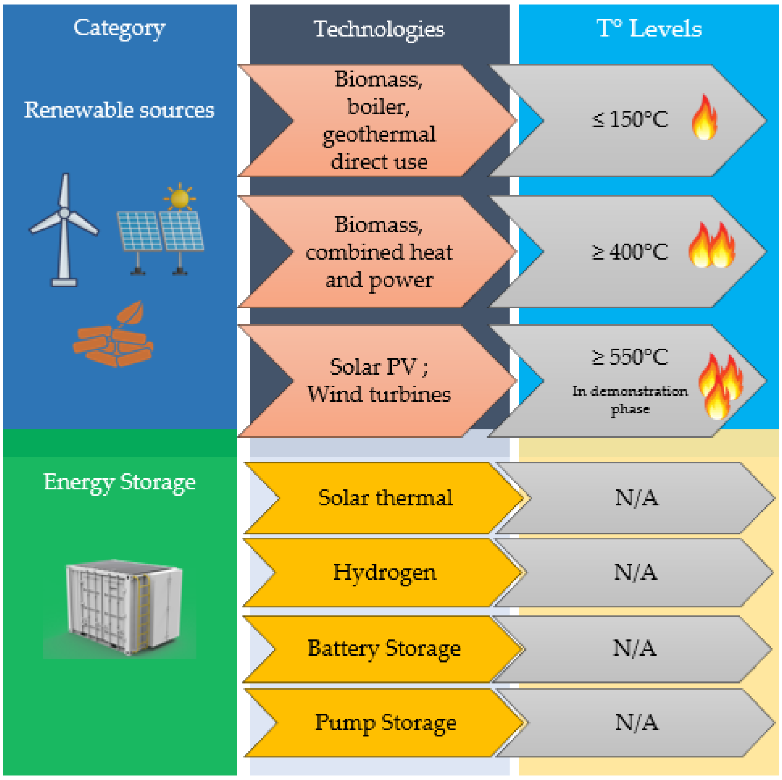

Figure 5. Current accessible and economical RE technologies.

The use of diesel fuel in power-reliant Canadian mining activities can be gradually supplanted, at least partially, by harnessing renewable energy sources. Comminution is a significantly energy-consuming mining process that involves mechanically reducing minerals and/or rock to predetermined sizes [48]. As per [49], comminution constitutes approximately 15% of the energy consumption for iron mining and around 21% for gold extraction. Interestingly, transitioning to renewable energy sources is relatively straightforward for these processes because comminution is predominantly electric. Moreover, investigations in [50] underscore that underground mining ventilation systems, such as those found in gold mines, contribute significantly to electricity consumption, accounting for approximately 20% of the overall energy usage.

Renewable energy (RE) sources, encompassing solar, wind, and geothermal energy, are increasingly emerging as viable solutions for off-grid and remote mining operations. The successful integration of clean energy to power the Diavik and Raglan mines in Canada's Arctic region exemplifies the potential of this approach. Another instance is the repurposed SunMine mine in British Columbia, which capitalizes on solar energy. Furthermore, geothermal energy as a sustainable power source has demonstrated its efficacy, as evidenced by the Éléonore mine project in Quebec, which can cover up to 35% of mining energy requirements. Notably, reference [51] highlights the potential impact of employing 21 MW of geothermal energy, supplemented by heat pumps, resulting in annual savings of 19,000 tons of carbon dioxide and CAD 1.5 million for Canadian mines. Remarkably, fluid temperatures as low as 22 °C can suffice for this application.

4.2. Replacing Diesel with RE for Transportation

To illustrate, a notable fraction of approximately 10% of the energy requisites for both iron ore and gold mining is allocated to transportation and hauling operations [52]. Since diesel fuel remains a prominent energy source for these functions, particularly in truck hauling, integrating renewables into material handling presents notable challenges. In Canada, employing biodiesel within mining encounters certain hurdles. High biodiesel blends, particularly those derived from non-soy substrates, may undergo gelation in cold weather conditions [53]. However, strategies that are employed to counteract cold-sensitive compounds can also be applied to circumvent gelling issues. Several biodiesel exporters currently employ this approach to warm personalized train carriages. Moreover, storing biodiesel within heated, sealed, or underground tanks within mining sites is a viable solution. Other tactics include housing biodiesel trucks within heated structures, incorporating heaters for fuel line filtration systems, deploying additives that mitigate the impact of cold temperatures, and adjusting blends based on seasonal variations. An example is at the Stillwater Mine, where B70 is utilized for all vehicles during the summer, transitioning to B20 for surface-parked vehicles in the winter.

However, a noteworthy development in the Canadian industry involves exploring battery-powered trucks to curtail fossil fuel consumption [54]. This progressive shift aligns with the industry's pursuit of sustainable alternatives.

4.3. Making Hydrogen with RE

Hydrogen plays a multifaceted role within the mining sector, serving various purposes such as high-temperature heat generation, electricity production, feedstock, fuel for vehicles and mining equipment, and energy storage. Currently, the dominant sources of hydrogen production are oil, coal, and natural gas [55]. Surplus energy can be efficiently transformed into hydrogen and stored for later utilization. Notably, excessive electricity can undergo conversion into hydrogen and be stockpiled for deployment in other mining operations that possess the capacity to integrate intermittent-output renewable energy technologies, such as solar and wind. For instance, the Canadian Raglan Mine has transitioned from diesel to wind power and energy storage [56], exemplifying the industry's shift towards more sustainable energy alternatives.

4.4. Electrifying Communities Nearby

Mining enterprises have historically erected essential infrastructure to cater to the needs of remote mining communities, including electricity supply for housing employees. By leveraging this existing infrastructure, mining companies possess the potential to significantly enhance electrification efforts by extending these services to nearby villages [57].

Capitalizing on economies of scale, mining entities can leverage their substantial power consumption and financial capabilities to establish larger-scale power plants than required for mining operations. This approach enables the extension of electricity access to adjacent communities at an economically viable rate. This endeavor could manifest as a novel micro-grid initiative, where electricity generation from renewable sources is designed to serve both the mine site and the neighboring populace. Alternatively, it could augment existing power sources by contributing to a functional mini-grid setup. A pertinent example is integrating renewable energy into a diesel-driven mini-grid that caters to a mining village. This approach curtails diesel expenditures and bolsters system reliability [58].

5. Electrification Alternatives in Canadian Mines

The shift towards electrification within the Canadian mining sector is already underway. Both ongoing and upcoming mining ventures in Canada are actively transitioning to renewable energy sources and incorporating battery energy storage to meet their electricity demands. Numerous forward-thinking Canadian enterprises are channeling investments into fully electric or hybrid electric vehicles to substitute diesel vehicles, curtail costs, diminish pollution, and embrace clean technologies for a more prosperous and ecological future [59–65]. However, this transition also ushers in infrastructure, maintenance, and operational challenges mine operators must contend with. Currently, a predominant focus within Canadian mining operations centers around electrifying their haulage systems. This initiative is highlighted by converting several heavy-duty truck prototypes into electrically powered alternatives actively integrated into service. Table 3 overviews Canadian mines' most advanced battery electric vehicle (BEV) electrification projects.

Table 3. An overview of Canadian mines that have integrated a fully electrified vehicle.

Project	Operator/Owner	Fleet Description
Borden Lake, Ontario	Goldcorp	Canada's first fully electric underground mine (fully electric fleet)
Macassa Mine in Kirkland Lake, Ontario	Agnico Eagle	Twenty-two battery electric scoops with 6 × Z50 trucks (a 50 tonne-battery-powered haul truck)
Onaping Depth Nickel-Copper Project, Ontario	Glencore Canada	An entire fleet of Epiroc battery-electric mining equipment (scoop tram loader, Minetruck hauler, Boomer face drilling rig, Cabletec rock bolting rig, and drill rig)
Lamaque Gold Mine, Quebec	Eldorado Gold	Two Sandvik TH550B battery-electric trucks
NMG open-pit, Quebec	Nouveau Monde Graphite	One × 40-tonne Western Star 6900XD
Brucejack Mine, British Columbia	Newcrest Mining	12 electric haul trucks
Mcllvenna Bay Project, Saskatchewan	Foran Mining Corporation	Fleet of 20 BEVs, including trucks, loaders, and drill
BHP Jansen Potash Project, Saskatchewan	BHP Group	Ten underground battery electric loaders and one electric tethered loader

5.1. Installation of a Trolley-Assist System for Diesel-Electric Trucks

Trolley-assist technology has been in existence for a considerable duration. During the energy crisis of the 1970s, sparked by events such as the Yom-Kippur War in 1973 and the Iranian Revolution in 1979, which disrupted oil supplies and led to scarcity and price surges for Western nations reliant on Middle Eastern energy exports, various mining companies explored trolley assist as a means to reduce their dependency on diesel fuel [66]. Although trolley assist offers advantages such as emission reduction, enhanced cycle times, and increased productivity, it failed to gain widespread traction. Multiple factors have contributed to the limited adoption of trolley assist, as outlined in [66]. Historically, diesel prices remained lower than today, and until recently, the mining industry lacked substantial incentives to mitigate its environmental impact.

However, the landscape has shifted with Canada's recent adoption of stringent climate change regulations and the implementation of carbon taxes. This has prompted the emergence of trolley-assist system installations in mines across the globe, including notable instances such as the Boliden Aitik mine in Sweden [67]. In Canada, only one mine has successfully integrated this technology into its operations. The Copper Mountain mine in southern British Columbia introduced a one-kilometer electric trolley-assist system in the spring of 2022. This innovative system aids 11 full-size hybrid Komatsu trucks in hauling ore uphill from the main mining pit to the primary crusher of the operation [68], as depicted in Figure 6.

(a) (b)

Figure 6. (**a**) The overall view of trolley-assist system installation at the Copper Mountain mine in B.C., Canada. (**b**) Haul trucks connected to the trolley-assist system network in action at the Copper Mountain mine [68].

With the recent implementation of the trolley-assist system at the Copper Mountain mine, there are optimistic expectations regarding fuel savings and emissions reductions. The company anticipates that each truck will be able to displace approximately 400 L of diesel per hour or around a tonne of CO_2 emissions. Despite the substantial CAD 40 million investment required for the integration of this innovative system into their operations, the company has identified compelling justifications for this endeavor:

1. Increasing Carbon Taxes: Adopting trolley assist can substantially mitigate Copper Mountain's carbon tax liabilities as these taxes continue to rise.
2. Escalating Diesel Costs: Using the trolley-assist system, each hybrid Komatsu haul truck consumes 400 L of diesel (equivalent to 1 ton of CO_2) per hour. Additionally, transitioning to clean power sourced from BC Hydro offers a more predictable cost structure than diesel's unpredictable availability and pricing fluctuations.
3. Enhanced Efficiency: Deploying hybrid trucks equipped with trolley assist translates to more efficient mineral transportation within shorter time frames.
4. Reduced Environmental Impact: With the support of the BC Government, Copper Mountain is aligning with efforts to bestow "responsible metals" credentials on their products as they traverse the supply chain. This designation positions these items for premium trading, ultimately augmenting their value.

According to ABB [69], trolley-assist systems can yield a remarkable reduction in diesel consumption of up to 90%, leading to lowered energy costs and simultaneously minimizing environmental footprints. Electrified trucks exhibit higher speeds and improved incline performance, enhancing operational efficiency.

5.2. Integration of In-Pit Crushing and Conveying Systems

In-Pit Crushing and Conveying (IPCC) systems consist of various components, including crushers, entirely mobile in-pit conveying systems, stationary conveyors, conveyor junctions, waste-spreading tripper cars, waste-spreading slewing spreaders, and mineralized material radial stackers [70], as depicted in Figure 7. Alternatives to the IPCC framework exhibit diverse configurations. There are three primary types of IPCC systems, each characterized by its distinct attributes. Based on the information presented in Table 4, the features of each system align with one of three main categories: fixed, semi-mobile, and fully mobile systems [71–74].

Table 4. Illustration of In-Pit Crushing and Conveying System Characteristics.

IPCC Type	Fixed	Semi-Mobile	Fully-Mobile
Crusher type	Jaw or gyratory	Twin roll or sizer	Twin roll or sizer
Relocation times	Never or rarely	Every 6-18 months	As needed
Feed systems	Shovel-trucks	Shovel-trucks and dozers	Shovel
Application	Deep hard rock mine ore	Not common in deep rock mine ore or waste	Not common in deep rock mine ore or waste

Compared to truck shovel (TS) options, IPCC systems offer a range of advantages supported by research reviews and real-world production experiences at mine sites [75–77]. The benefits of IPCC systems include:

- Energy Savings: Conveying minerals through conveyors inherently demands less energy per unit weight than transporting them via trucks [78]. Notably, only 39% of the energy utilized in a truck cycle is dedicated to moving the payload, with the remaining 61% allocated to moving the vehicle's weight. Additionally, by relying on electricity-based methods, IPCC systems can reduce a mine's reliance on diesel fuel.
- Environmental Impact (Dust and Noise): Implementing IPCC systems can reduce noise pollution as conveyors generate less noise than conventional diesel-powered trucks. Moreover, reducing the number of trucks on the road can significantly diminish the dust emissions sources, positively impacting the environment [78].
- CO_2 Emissions: IPCC systems can substantially reduce CO_2 emissions by facilitating fuel switching. A noteworthy example is found in a Brazilian iron ore mine that has integrated two fully mobile IPCC systems, collectively capable of handling 7800 t/h, resulting in an estimated reduction of 60 million liters of diesel consumption annually [79]. This approach aligns with utilizing renewable energy sources, such as hydroelectric, solar, and wind-based electricity, to transform IPCC into a decarbonized transport mining system.
- Operational Costs: As mining activities escalate, waste dumps grow, and the pit becomes deeper. This progression leads to longer truck haul cycles and increased demand for additional trucks to meet production requirements. Truck hauling is frequently perceived as more costly than IPCC methods, particularly with increased distances and elevation [80]. Embracing an IPCC system over a truck haulage system can significantly reduce material transport operating expenses (OPEX), owing to potential savings from energy conservation, workforce reduction, enhanced weight efficiency, and lower maintenance costs.
- Production Efficiency: The continuous transportation approach offered by IPCC systems often translates to increased production rates. This approach involves transporting ore or waste materials to designated locations consistently and efficiently [81]. A comprehensive comparison of the two systems (TS/IPCC) based on time utilization, operational time, and useful operating time metrics underscores the greater production efficiency associated with conveyor haulage when considering overall equipment performance.

Figure 7. (**a**) Fixed IPCC system; (**b**) semi-mobile IPCC system; and (**c**) fully mobile IPCC system [81].

6. Challenges for RE and Transport Electrification in Canadian Mines

This section delineates the key impediments that impede the seamless integration of renewable energy (RE) and electrified transportation into the Canadian mining sector. The ensuing discussions present these hindrances through five distinct categories: (1) technical challenges; (2) expertise and logistics; (3) financing; (4) research and development; and (5) business models. This section concludes with a table presenting the different challenges of integrating RE and electrifying Canadian mining sites.

6.1. Technical Challenges

The foremost technical challenges associated with solar and wind energy pertain to their inherent unpredictability and variability. These renewable energy sources can only be harnessed during sunny or windy conditions, with power generation contingent upon factors such as cloud cover and wind speed. This poses a significant incongruity with the continuous and stable power supply demanded by mining operations [82]. In addition, icing is another challenge for wind turbines and solar panels, due to very cold and long winter temperatures (up to −40 °C). This may significantly reduce energy production and affect maintenance due to restricted access. The evolving landscape of battery storage costs can potentially revolutionize the intermittency and variability quandary. However, in the immediate term, battery storage is not poised to entirely supplant diesel utilization in off-grid scenarios [83]. Furthermore, the feasibility of battery technology over alternatives remains uncertain, particularly given the harsh winter climate prevalent in Canada. In addition to these concerns, the comparative land footprint of renewable energy installations is notably more extensive than that of conventional power facilities. Comprehensive estimates of land use intensity for various RE sources are illustrated in Table 5 as per data from [84].

Table 5. Land use by RE sources compared to fossil fuel [84].

Product	Primary Energy Sources	Land Use Intensity m^2/MWh
Electricity	Nuclear	0.1
	Wind	1.0
	Geothermal	2.5
	Solar PV	10
	Solar-concentrated solar power	15
	Biomass (crops)	500
Liquified Fuel	Fossil fuel	0.4
Biofuels	Corn (maize)	230
	Soybean	400
	Cellulose, short rotation coppice	500

Moreover, the potential of renewable energy (RE) is intricately tied to geographical location, necessitating a meticulous analysis of site-specific variables. In remote areas lacking proximate weather stations, procuring supplementary wind speed and solar rate data spanning one to two years may be imperative. This extended data collection is essential for establishing an accurate average production projection incorporating seasonal fluctuations.

However, battery electric vehicles (BEVs) are not impervious to technical obstacles. Notably, the frigid Canadian winter can extend charging durations due to its impact on the electrochemical reactions within EV batteries, potentially resulting in decreased production rates [85–87]. This could prompt companies to consider augmenting their electric fleet and charging infrastructure to compensate for prolonged charging times and the increased number of vehicles. Additionally, introducing high-voltage equipment, unfamiliar to most employees, raises the specter of technical issues such as arcing and explosions stemming from inadequate maintenance or mishandling of batteries [88–90].

6.2. Expertise and Logistics

While mining enterprises exhibit an unwavering commitment to elevating health and safety standards—entrenched within the industry's ethos—this diligence does not uniformly translate to power management systems and energy conservation initiatives. Mining conglomerates face a shortage of essential technical proficiency in renewable energy (RE) and hybrid systems. The expertise in designing, operating, repairing, and maintaining diesel-powered systems prevalent in off-grid mining operations lies predominantly within the purview of mining professionals and established suppliers. Regrettably, this scenario constrains the seamless integration of renewable power [91]. Although power providers catering to the sector are gradually introducing hybrid options, only a few mines in Canada, such as Raglan and Diavik, have embarked on the journey of amassing experiential knowledge in RE implementation.

In logistics, Canadian mining corporations have mastered the formidable challenge of supplying heavy fuel oil or diesel to remote mine sites, a feat particularly pronounced in border regions such as the Arctic. Notably, the Diavik mine exemplifies this feat, where ice roads remain the exclusive conduit for truckers and heavy machinery during certain winter weeks. Integrating renewables in such locales can alleviate logistical complexities and expenses associated with fuel transportation [92]. For instance, Diavik's environmental sustainability report underscores the achievement of its 9.2 MW wind farm, which contributed 11% of the mine's power in 2014 and mitigated 5 million liters of diesel consumption. Although seemingly impressive—equivalent to 37 fuel trucks traversing ice roads—this achievement pales when juxtaposed against the aggregate fuel usage at the mining site, encompassing electricity and other fuel-consuming operations such as the truck fleet (Figure 8). Furthermore, the integration of renewable plants entails additional on-site personnel and meticulous planning, exemplified by Glencore's conscientious deliberations concerning the transportation of wind farm components to its Raglan mining site and the management of control and maintenance amid challenging circumstances characterized by restricted road access and limited communication avenues [93].

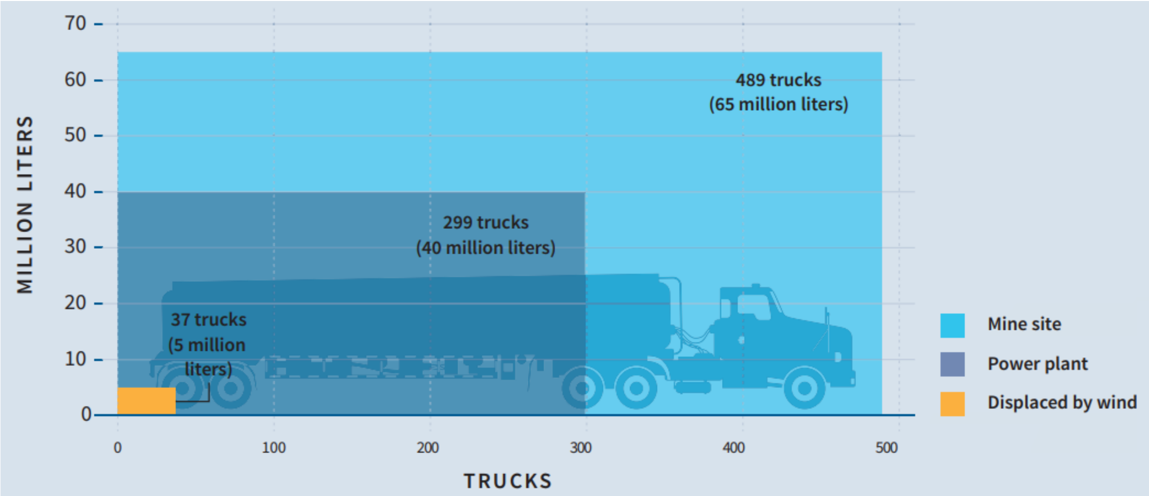

Figure 8. An illustration of the Canadian Diavik mine's fuel trucks [93].

The adoption of battery electric vehicles (BEVs) within the Canadian mining industry remains relatively nascent, resulting in a scarcity of experienced trainers in this domain [94]. BEVs also operate with reduced noise levels, potentially heightening the risk of accidents where workers inadvertently encounter the vehicle [95]. Such circumstances may necessitate the establishment of novel subterranean communication protocols and further investments in innovative technologies to propel the mine toward full connectivity [95–97].

6.3. Financing

The initial capital outlay for establishing a renewable energy plant surpasses the cost of incorporating generators into a diesel-based facility, and this cost differential is projected to persist in the foreseeable future [98–100]. This financial aspect assumes considerable significance from a cash flow perspective, especially when contemplating a self-generation setup. The higher upfront costs associated with renewable solutions could extend the timeline for recovering the initial invested capital. Such a capital investment shortfall could be particularly detrimental, considering the benefits of augmenting renewable energy penetration or disseminating electricity to proximate communities [101].

While there are economies of scale to be gained by constructing large-scale solar and wind installations, these advantages are still intertwined with augmented initial capital outflows, subsequently deferring capital recouping. This is further compounded if the mining enterprise shoulders the distribution expenses tied to local electrification efforts, leading to escalated capital expenditures [102].

To circumvent hefty capital expenses, one viable avenue is outsourcing the renewable project to an Internal Power Producer (IPP). However, financial constraints become a significant hurdle when transferring renewable energy (RE) project ownership to an IPP [103]. Many RE IPPs lack the equity to underwrite the project's initial capital requirements. This predicament could result in banks rejecting loan requests for the RE project due to insufficient capital or imposing elevated interest rates to mitigate investment risks.

Lenders scrutinize the mining company's risk profile and the power purchase agreement (PPA) duration in instances where the mining entity acts as the off-taker. The PPA's duration must be sufficiently extended to ensure the profitability of the renewable energy endeavor. Consequently, the anticipated lifespan of the mining operation emerges as a pivotal factor in determining the viability of renewable projects, influencing the time horizon that the mining firm can commit to [104]. Table 6 presents the requisite timeframes for various power solutions.

Table 6. Viability of technologies as a function of mine lifespan [105].

	Lifespan: 3–7 Years	Lifespan: >10 Years
Diesel generators	✓	✓
Gas turbines	✓	✓
Solar PV	Unlikely	✓
Wind turbines	Unlikely	✓
Concentrated solar power	Unlikely	✓

For a renewable energy project to yield cost-saving potential relative to less capital-intensive power sources such as diesel, the projected lifespan of the mine should align with the approximate 20–25-year operational span of a solar/wind plant. The allure of renewable energy alternatives for off-grid mines diminishes with shorter mine lifespans [93,105].

6.4. Research and Development

The Canadian mining sector needs cost-effective solutions to embrace affordable, long-duration energy storage systems for scaling up renewable energy adoption, as well as for incorporating clean heat sources at high temperatures. Additionally, green hydrogen production emerges as a promising avenue for low-emission heating or feedstock purposes, offering the potential for research and innovation [106–108]. Similar prospects lie in developing lighter batteries with enhanced autonomy for industrial applications [109]. Furthermore, the integration of Blockchain technology, which remains largely underutilized in Canadian mines, could enhance transparency, simplicity, and security in investments. Blockchain could also enable the tracing of "green" minerals, thereby contributing to mining sector operations [110,111]. Instead of leading these initiatives from scratch, the Canadian mining industry could achieve significant strides in RE adoption by embracing technologies and processes proven effective in other sectors.

6.5. Business Models

The limited availability of flexible renewable energy solutions and the financial constraints many mining corporations face, especially smaller to medium-sized enterprises, contribute to a sense of caution. Policy support will be pivotal in shaping agreements, such as power purchase agreements, aligning incentives and legal frameworks, and fostering net metering for grid-connected mining operations. Analyzing the advantages and disadvantages of RE incorporation can aid governments and stakeholders, including the financial sector, in making informed decisions to support these endeavors.

6.6. Main Challenges of Integrating RE and Electrifying Canadian Mine Sites

The primary difficulties of integrating renewable energies and electrification at Canadian mine sites are summarized in Table 7 with the objective to better explain the findings of Section 6.

Table 7. Comparison of the main challenges to integrating RE and electrifying mine sites in Canada.

Types	Decarbonization Solutions	Main Challenges
Renewable energies	Biofuels	• May undergo gelation in cold weather • Require heated storage structure
	Solar PV	• Require a large plot of land • Dirt, snow, and ice accumulating on solar panels can block the sun's rays, reducing the amount of electricity generated. • Not profitable if mine lifespan is less than 10 years
	Wind turbines	• Accumulation of ice on wind turbine blades resulting in reduced power output and increased rotor loads • Cold weather shutdown to prevent equipment failure • Limited or reduced access for maintenance activities • Not profitable for a short mine lifespan ($\leq$10 years)
Electrification	TA	• Longer haulage distances and steeper grades state a challenge for more powerful transporting systems. • Keeping haul trucks as small as possible is also desired, so power consumption goes to ore transport only.
	IPCC	• It produces excessive noise and light pollution that can negatively affect the quality of life of humans and wildlife nearby • Generates thousands to millions of tons of waste and requires a large disposal area to accommodate them.
	BEV	• Lack of experience among technicians, trainers and mining engineers in dealing with high-voltage equipment • The quieter operation of BEVs increases the risk of collisions with workers • Battery efficiency is affected by cold climates

7. Conclusions

This review examines the progress of energy transition within Canadian mines as they strive to meet the obligations of the Paris Climate Change Agreement. While several active projects are underway to integrate renewable energy sources such as wind, solar, and storage systems, particularly in off-grid mining operations, the predominant focus within the Canadian mining industry is presently centered on electrifying their transportation fleets through substantial investments in electric heavy-duty trucks. This emphasis is driven by the substantial portion (30–40%) of operating costs for Canada's mines, both underground and open-pit, stemming directly from diesel usage in transportation systems. Moreover, the ongoing RE initiatives at Raglan and Diavik mines, although commendable, only account for a modest 10–12% of their energy requirements, indicating room for growth.

The review also highlights the numerous challenges in integrating RE into off-grid Canadian mine sites. The spatial demands and operational intricacies associated with RE installations and the perceived expertise and management hurdles present notable obstacles for many Canadian mines. The complex logistics of implementing RE at remote sites further complicate large-scale integration, impeded by transportation constraints, skilled labor availability, infrastructure limitations, adverse weather conditions, and communication challenges. Furthermore, the economic viability of RE implementation is profoundly influenced by the projected lifespan of the mining operation, cautioning against introducing RE solutions when a mine has a relatively short exploration horizon of 3–7 years. On the contrary, it becomes more feasible to invest in RE systems when the mine's operational life extends beyond a decade.

While IPCC and trolley-assist (TA) systems hold promise for decarbonizing Canadian mines, the review has encountered limited evidence regarding the widespread integration of these decarbonization technologies. The integration of IPCC is yet to be entirely ascertained, and TA integration remains limited, exemplified by a single instance at the Copper Mountain mine in British Columbia.

Finally, the review underscores the technical challenges posed by battery electric vehicles (BEVs) pose. Concerns raised by experts in the field include the lack of experience among technicians and mining engineers in dealing with high-voltage equipment, elevating the risk of electric fires and battery-related accidents. The shortage of trainers in this evolving field further compounds these challenges. Additionally, the quieter operation of BEVs increases the risk of collisions with workers, necessitating the development of new communication protocols and increased investment in cutting-edge technology to advance toward a fully connected mine. It is worth noting that Canada's harsh winter weather conditions can impact production efficiency, as battery performance tends to decline in colder temperatures compared to the summer months.

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