Canadian Energy Outlook

The Decarbonization of Off-Road Transport in Net-Zero Pathways

3rd edition

INSTITUT DE L'ÉNERGIE TROTTIER

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About the Institut de l'énergie Trottier (IET)

The Institut de l'énergie Trottier (IET) was created in 2013 thanks to an exceptional donation from the Trottier Family Foundation to Polytechnique Montréal. Since then, it has been involved in every energy debate in the country. At the source of major collective reflections, the team mobilizes knowledge, analyzes data, popularizes issues and recommends fair and effective plans, simultaneously contributing to academic research and training. Its independence gives it the neutrality essential to the collaborative approach it advocates, facilitating work with the players most likely to advance the energy transition, while allowing it to be freely critical when relevant.

As the initial 10-year mandate came to an end, the Trottier Family Foundation decided to renew its confidence in the IET and made a new donation. Given the scope of the IET's activities and its status as a key player, its mandate was extended. The team will thus be able to continue offering science-based advice and enriching societal dialogue in order to advance the way we produce, convert, distribute and use energy.
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Citation
Langlois-Bertrand, S., Mousseau, N. (2025). The Decarbonization of Off-Road Transport in Net-Zero Pathways. In Langlois-Bertrand, S., Mousseau, N., Beaumier, L. (Eds.), Canadian Energy Outlook 3rd edition, Institut de l'énergie Trottier – Polytechnique Montréal.

version 20250507
ISBN: 978-2-924597-29-3

Executive Summary

The decarbonization of the Canadian economy to achieve the net-zero objective by 2050 requires rapid and profound transformations in all emissions sources. In efforts to accelerate decarbonization and the implementation of net-zero pathways for Canada as a whole, off-road transport (see Box ES.1) has so far largely fallen between the cracks. One reason for this oversight is the broad and eclectic nature of the sector, as it is largely used as a residual category when analyzing both energy demand and GHG emissions. As a result, the exact services provided in the off-road category vary substantially, from very large machinery in quarries to handheld leaf blowers.

Box ES.1 – Defining off-road

We refer to off-road transport as mobile or handheld equipment, which includes machinery but also vehicles not registered for use on public roads. This category is present across all sectors of industry (e.g., asphalt pavers), residential and recreational services (e.g., leafblowers), agriculture (e.g., farm tractors) and commercial operations (e.g., turf equipment), including airports and public administration.

Despite this lack of attention, emissions from the off-road transport category in Canada's National Inventory Report (NIR) represented 28.8% (56.4 $MtCO_2e$) of total emissions from the transport sector nationwide in 2022. Moreover, in the latest edition of the Canadian Energy Outlook (Langlois-Bertrand et al. 2024), projections to 2050 show a growth of 13% of these emissions in the reference scenario, making it the main source of emissions for the transport sector by mid-century, slightly larger than road transport. In net-zero scenarios modelled in that same report, this increased role is even more dominant in relative terms: despite a large reduction of off-road transport emissions (-57% by 2050), their relative share grows to represent 57% of total remaining transport emissions. This growth reflects a combination of the high cost for many low-carbon solutions in the sector, a limitation in technological solutions available to proceed, as well as a lack of policy and regulatory measures to orient the needed transformations.

This document is intended to serve as a background paper for discussions on strategies to decarbonize off-road transport in Canada in order to and make this sector a key contributor to a net-zero pathway. It starts by presenting a detailed profile of off-road transport emission sources. Building on information gathered from a review of institutional and academic literature on off-road decarbonization and bonified by conversations during recent IET work with experts in the field involved in the decarbonization of off-road vehicles and machinery, it then provides an overview of some of the key challenges and opportunities inherent in developing a decarbonization roadmap in each sector for off-road transport needs.

The review focuses on decarbonization options for specific subsectors as well as on the challenges associated with some electricity-based technologies. The descriptions are not intended to be exhaustive but rather to present several key off-road transport trends and ideas relating to the most pressing questions facing organizations and governments attempting to decarbonize their operations or sectors altogether. Since most of the literature available examines non-Canadian context, the added contributions from exchanges with experts formed a basis for discussing parts or forms of these challenges in the more specific context of Canada's sectors.

When putting these insights together, it is possible to identify cross-cutting issues in the design of policies for decarbonizing off-road transport in the Canadian context. For instance, a first challenge is whether a **replacement technology** that is non-emitting while offering workable conditions for the service offered **is readily available**. Another is that on-emitting equipment may present **additional constraints and requirements**, such as range and charging time for electricity-powered equipment. Furthermore, alternative energy sources to propel new equipment may require **significant additional infrastructure**.

As a result, developing a strategic approach to the decarbonization of off-road transport must take into account the fact that services provided by off-road equipment are very diverse, which makes it necessary to build a comparative assessment of these challenges, their importance for specific off-road services, the opportunities in some Canadian contexts and the benefits of each option beyond the reduction of GHG emissions and contribution to a net-zero pathway for Canada. With this assessment in hand, **we propose to design the strategic approach using a stepwise learning process. Such an approach should prioritize immediate opportunities, designing targeted pilot projects in a way that maximizes learning opportunities for off-road activities, and identify areas where decarbonization pathways are most difficult in the short and medium term and where significant exploration will help clarify the needs.**

With this in mind, the steps of this approach should follow four higher-level principles:

1) Maximize electrification where possible: of the different possible energy source switches, moving from diesel to electricity is the most compatible with net-zero objectives.
2) Explore other low-carbon energy sources based on potential co-benefits and nearby infrastructure availability.
3) Anticipate information gathering needs for technology options and share this information with relevant actors and stakeholders.
4) Launch pilot projects to test options. Based on the comparative assessment of specific decarbonization options and on the three above criteria, pilots should be chosen and designed to maximize the potential for learning and to spill over into other sectors where decarbonization options face similar challenges.

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1. Introduction

The decarbonization of the Canadian economy to achieve the net-zero objective by 2050 requires rapid and profound transformations in all emissions sources. Since energy production and use is directly responsible for over 80% of the country's greenhouse gas (GHG) emissions, most of the emission reduction efforts have so far focused on transforming the energy system. These efforts include initiatives to exchange incumbent energy sources for non-emitting ones, reduce the GHG footprint of energy transport and distribution operations, and make energy use more productive.

While there is no shortage of challenges inherent in transformation pathways to build a net-zero energy system, the transport sector often attracts a significant amount of attention because of its strong path-dependency on fuel infrastructure, as well as constraints and obstacles to deep transformations tied to the cost of and technology for alternative solutions.

To date, the overwhelming share of political and public attention devoted to decarbonizing the transport sector has been focused on road transport. There are certainly good grounds for understanding this prioritization: the decarbonization of passenger transport is already possible on a large scale given the availability and relatively low cost of electric vehicles. As well, zero-emission technologies for road transport of merchandise, despite being less mature as well as more costly and limited on a commercial scale, are largely recognized. However, decarbonizing heavy transport subsectors outside of roads, especially marine and aviation, is difficult given the technological readiness level of alternative fuel sources. As a result, most of the attention is focused on fostering innovations that could have a longer-term impact.

In parallel, off-road transport has so far largely fallen between the cracks of decarbonization efforts. One reason for this oversight is the broad and eclectic nature of the sector, as it is largely used as a residual category when analyzing both energy demand and GHG emissions. As a result, the exact services provided in the off-road category vary substantially, from very large machinery in quarries to handheld leaf blowers.

While the definition of off-road transport varies,[1] in this report we refer to it as mobile or handheld equipment, which includes not only machinery but also vehicles not registered for use on public roads.[2] This category is present across all sectors of industry (e.g., asphalt pavers), residential and recreational services (e.g., leaf blowers), agriculture (e.g., farm tractors) and commercial operations (e.g., turf equipment), including airports and public administration.[3]

Despite this lack of attention, emissions from the off-road transport category in Canada's National Inventory Report (NIR) represented 28.8% (56.4 $MtCO_2e$)[4] of total emissions from the transport sector nationwide in 2022. Moreover, in the latest edition of the Canadian Energy Outlook (Langlois-Bertrand et al. 2024), projections to 2050 show a growth of 13% of these emissions in the reference scenario, making it the main source of emissions for the transport sector, slightly larger than road transport. In net-zero scenarios modelled in that same report, this increased role is even more dominant in relative terms: despite a large reduction of off-road transport emissions (-57% by 2050), their relative share grows to represent 57% of total remaining transport emissions. Given the nature of this modelling exercise, this growth reflects a combination of the high cost for many low-carbon solutions in the sector, a limitation in technological solutions available to proceed, as well as a lack of policy and regulatory measures to orient the needed transformations.

This document is intended to serve as a background paper for discussions on strategies to decarbonize off-road transport in Canada and make it a key contributor to a net-zero pathway. It first presents a detailed profile of off-road transport emission sources,[5] followed by an overview of some of the key challenges and opportunities inherent in developing a decarbonization roadmap in each sector for off-road transport needs. A list of proposals to design a decarbonization strategy concludes the report.

[1] See Section 2.1 of this report.
[2] For a similar approach, see USDOE-USEPA (2024).
[3] Table 1 provides a more comprehensive list of equipment and vehicles.
[4] This includes emissions from the operation of pipelines.
[5] We would like to extend special thanks to Environment and Climate Change Canada for its help and contribution, including data that were essential to build the detailed sectoral GHG profiles for off-road services set out below.

2. Profile of the off-road transportation sector

2.1 Defining off-road

The definitions of off-road vary considerably in discussions on this type of transport. These differences may be partly attributed to the generic definitions sometimes used, which refer to off-road simply as vehicles designed especially to operate away from public roads. Even in some legal definitions, such as that provided by the Canadian Centre for Occupational Health and Safety, the term refers to vehicles used for both work and leisure and designed to be *primarily* off-highway and operated in rugged environments such as non-public roads and paths (CCOHS 2025). Another example is the interpretation offered in the Motor Vehicle Safety Regulations, which define off-road vehicles as being mainly used for recreational purposes or for transporting property or equipment exclusively on undeveloped road rights of way, marshland, open country, or other unprepared surfaces (Canada 2021).

Table 1 – Examples of equipment across categories of off-road transport

IPCC category	Economic sector	Equipment	
Off-road agriculture and forestry	Agriculture	• Farm tractors • Sprayers • Tillers • Mowers	• Balers • Irrigation sets • Swathers
	Forestry	• Shredders • Chain saws	• Skidders
Off-road commercial and institutional	Commercial and Other Institutional	• Chain saws • Turf equipment • Hydro power units • Lawn mowers • Leaf blowers/vacuums • Light commercial generator sets • Light commercial pressure wash • Light commercial pumps • Light commercial welders • Wood splitters	• Other lawn and garden equipment • Rotary tillers • Shredders • Snowblowers • Trimmers/edgers/cutters • Air compressors • Chippers/stump grinders • Lawn and garden tractors • Rear engine mowers
	Public Administration		
Off-road manufacturing, mining and construction	Total Mining and oil and gas extraction	• Bore/drill rigs • Concrete/industrial saws • Crushing/Proc/Equipment • Paving Equipment • Compactors • Sweepers/scrubbers • Tampers/Rammers • Aerial lifts • Asphalt pavers • Cement & Mortar Mixers • Concrete pavers • Cranes • Other construction equipment • Dumpers/Tenders	• Excavators • Rollers • Rough Terrain Forklifts • Rubber Tire Loaders • Skid Steer Loaders • Surfacing Equipment • Tampers/Rammers • Tractors/Loaders/Backhoes • Trenchers • Diesel Asphalt Pavers • Diesel Bore/Drill Rigs • Diesel Cement & Mortar Mixers • Crawler Tractors

The Canadian Off-Road Small Spark-Ignition Engine Emission Regulations (SOR/2003-355) define off-road engines more broadly as an engine that is "capable of being carried or moved, either by itself in or on a machine designed to be or capable of being carried or moved, that is self-propelled, that which serves a dual purpose by both propelling itself and performing another function, or that is designed to be propelled while performing its function" (Canada 2025).

Similarly, when it comes to GHG emissions in particular, the extent of the off-road transport category is broader in at least two ways: (1) it describes the vehicles and machinery that are not registered for use on public roads and (2) it uses the term "mobile equipment" as opposed to "vehicle" to enable the inclusion of several types of equipment that are not attached to buildings or sites but that nevertheless are not vehicles in any conventional way (for instance, lawnmowers, chain saws, and so on). Given the subject of this report, to be consistent with this approach, we use this broader category definition, as do other similar discussions of off-road transport for decarbonization pathways (US-DOE-USEPA 2024). In this context, vehicles are a subset of equipment.

IPCC category	Economic sector	Equipment	
Off-road manufacturing, mining and construction	Construction	• Bore/drill rigs • Concrete/industrial saws • Crushing/Proc/Equipment • Paving Equipment • Compactors • Tampers/Rammers • Asphalt pavers • Cement & Mortar Mixers • Concrete pavers • Cranes • Crawler tractors • Dumpers • Tenders	• Excavators • Other construction equipment • Rollers • Rough Terrain Forklifts • Rubber Tire Loaders • Skid Steer Loaders • Surfacing Equipment • Tampers/Rammers • Tractors/Loaders/Backhoes • Trenchers • Diesel Asphalt Pavers • Diesel Bore/Drill Rigs • Diesel Cement & Mortar Mixers
	Iron and Steel	• Forklifts • Industrial AC/Refrigeration • Other industrial equipment • Other material handling equipment	• Sweepers/Scrubbers • Terminal Tractors • Sweepers/Scrubbers • Tractors/Loaders/Backhoes • Diesel Aerial Lifts
	Cement	• Forklifts • Industrial AC\Refrigeration • Other industrial equipment • Other material handling equipment	• Sweepers/Scrubbers • Terminal Tractors • Sweepers/Scrubbers • Tractors/Loaders/Backhoes • Diesel Aerial Lifts
	Chemicals	• Forklifts • Industrial AC/Refrigeration • Other industrial equipment • Other material handling equipment	• Sweepers/Scrubbers Terminal Tractors • Sweepers/Scrubbers • Tractors/Loaders/Backhoes • Diesel Aerial Lifts
	Pulp and paper	• Forklifts • Industrial AC/Refrigeration • Other material handling equipment • Other industrial equipment	• Sweepers/Scrubbers • Terminal Tractors • Sweepers/Scrubbers • Tractors/Loaders/Backhoes • Diesel Aerial Lifts

In the NIR, the IPCC GHG emissions classification divides off-road sources of emissions into six sub-categories: agriculture and forestry, commercial and institutional, manufacturing, mining and construction, residential, and other.[6] Emissions reported by economic sector in the NIR are classified differently (see Section 2.2 below). While a complete and exhaustive listing of equipment within each category is beyond the scope of this document, we provide a list of examples for each sub-category in Table 1, indicating both the IPCC category as well as the economic sector they belong to in NIR tables.

IPCC category	Economic sector	Equipment	
Off-road manufacturing, mining and construction	Other manufacturing	• Forklifts • Industrial AC/Refrigeration • Other industrial equipment • Other material handling equipment	• Sweepers/Scrubbers • Terminal Tractors • Sweepers/Scrubbers • Tractors/Loaders/Backhoes • Diesel Aerial Lifts
	Smelting and refining, non-ferrous	• Forklifts • Industrial AC/Refrigeration • Other industrial equipment • Other material handling equipment	• Sweepers/Scrubbers • Terminal Tractors • Sweepers/Scrubbers • Tractors/Loaders/Backhoes • Diesel Aerial Lifts
	Oil Sands	• Crawlers • Excavators • Graders	• Trimmers/edgers/cutters • Lawn & garden tractors • Rear engine mowers
Off-road residential	Residential and Recreational	• Chain saws • Lawn mowers • Leaf blowers/vacuums • Lawn and garden equipment • Rotary tillers	• Trimmers/edgers/cutters • Lawn & garden tractors • Rear engine mowers • Snowblowers
Off-road other transportation	Residential and Recreational	• All-terrain vehicles • Go karts • Golf carts • Off-road motorcycles	• Snowmobiles • Inboards • Outboards • Personal watercraft
	Commercial and Other Institutional	• Vehicle carts • Utility vehicles	• All-terrain vehicles
	Public Administration	• Vehicle carts • Utility vehicles	• All-terrain vehicles
	Canadian Airlines	• Airport support equipment	
	Railways	• Railway maintenance	

[6] These emissions are reported in Table A9–2 in Canada (2024).

2.2 Comparison with economic sector classification

In the NIR, the categorization of off-road transport emissions constitutes one of the main differences between the classification by IPCC sectors vs. by economic sector, presented in Table A9–2 and Table A10–2, respectively (Canada 2024). In general, the latter classification associates off-road transport emissions with the economic sector responsible for the equipment producing them, while in the IPCC guidelines they are classified first under transport emissions and are then disaggregated by sector.

A further complication is the use of the "Off-road other transportation" category under the classification by IPCC sector, which is broken down into "Residential and Recreational," "Commercial and Institutional" and "Public Administration," in addition to including "Canadian Airlines" as well as "Railways." The use of the first three of these subcategories creates some confusion within other IPCC off-road categories because each is found not only in the main category, but also as a subcategory of "Off-road other transportation." For instance, some emissions from residential equipment are categorized under the "Off-road residential" IPCC category, while others are categorized in the "Residential and Recreational" subcategory of "Off-road other transportation."

Table 2 provides the correspondence between the off-road emissions categories under the IPCC classification and under the economic sector classification.

Table 2 – Correspondence of off-road emissions categorization under IPCC sectors and economic sectors classifications in the NIR

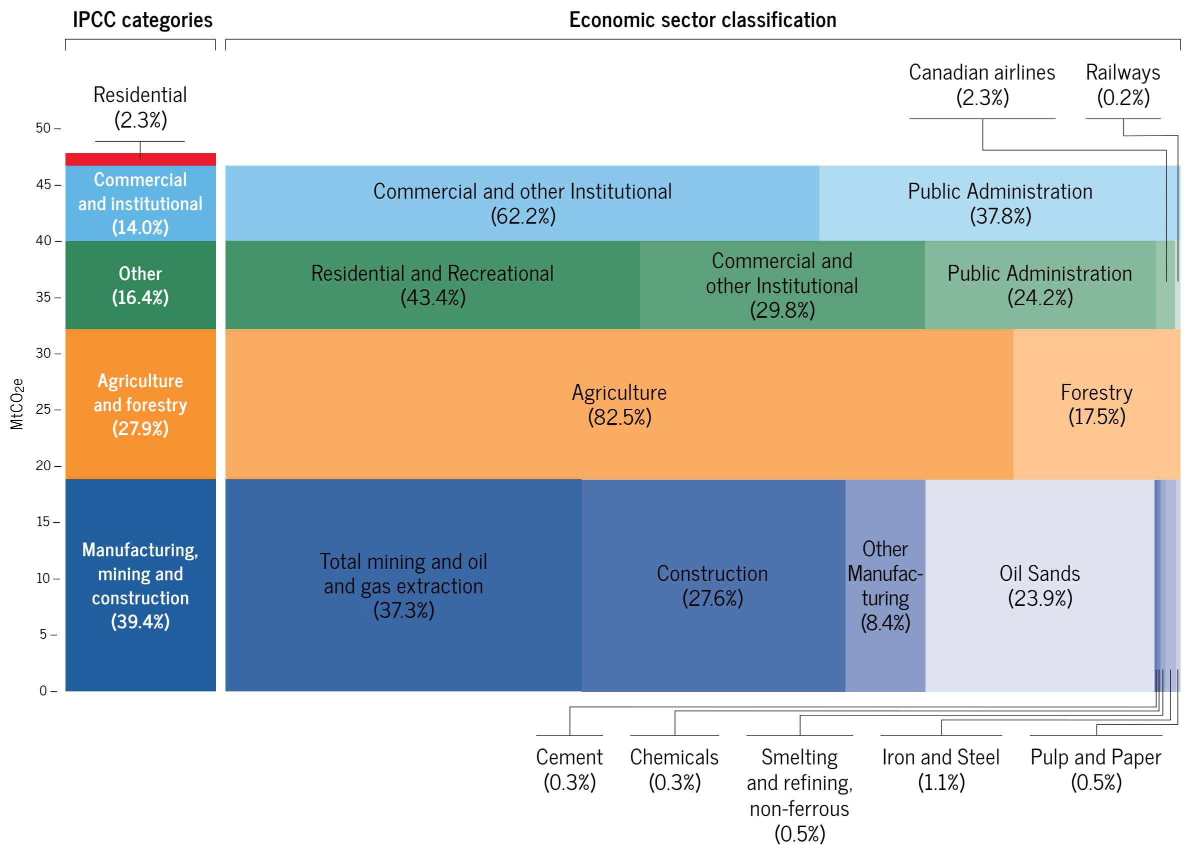
Economic sector	IPCC category				
	Agriculture and Forestry	Commercial and Institutional	Manufacturing, mining and construction	Residential	Other
Residential and Recreational				X	X
Commercial and Institutional		X			X
Public Administration		X			X
Canadian Airlines					X
Railways					X
Agriculture	X				
Forestry	X				
Total Mining and Oil and Gas Extraction			X		
Construction			X		
Iron and Steel			X		
Cement			X		
Chemicals			X		
Pulp and Paper			X		
Other Manufacturing			X		
Smelting and refining, non-ferrous			X		
Oil Sands			X		

2.3 GHG emissions breakdown

Figure 1 shows the high-level breakdown of emissions from off-road transport in the IPCC classification and the further breakdown of each IPCC category of emissions along economic sector classification. The main sources of off-road emissions are manufacturing, mining and construction (39.4%), along with agriculture and forestry (27.9%), with the rest almost evenly split between other (16.4%) and commercial and institutional (14.0%. The residential category is negligible in this categorization (2.3%).

A further breakdown along economic sector classification provides helpful detail. One example is the breakdown of agriculture and forestry into its two components, which shows that agriculture is actually responsible for 82.5% of emissions in this category, or 23.0% of total off-road emissions. Another helpful breakdown for industrial off-road emissions shows that within the manufacturing, mining and construction category, mining and oil and gas extraction (including oil sands) emit 61.2% of the total, with oil sands alone producing 23.9% of the total. Construction is another important source, at 27.6% within manufacturing, mining and construction. Most of the other industrial sectors emit only a very small share of the total.

Figure 1 – Off-road transport emissions, breakdown of IPCC categories by economic sector classification (2022)



Note : percentages in the left section (IPCC categories) represent the share of total off-road emissions; in the section on the right (economic sectors), each row shows the economic sector emissions breakdown of the corresponding IPCC category.

Given these insights, it is helpful to look at high-level breakdowns by economic sector only, which provide a more intuitive classification that regroups the categories into more readily identifiable sectors and activities. As Figure 2 shows, total off-road residential and recreational emissions amount to 9% of off-road emissions, with emissions from the commercial, institutional and public administration sector making up 23%. Agriculture represents a similar share (23%) that is also similar to mining and oil and gas extraction (including oil sands), which reaches 24%.

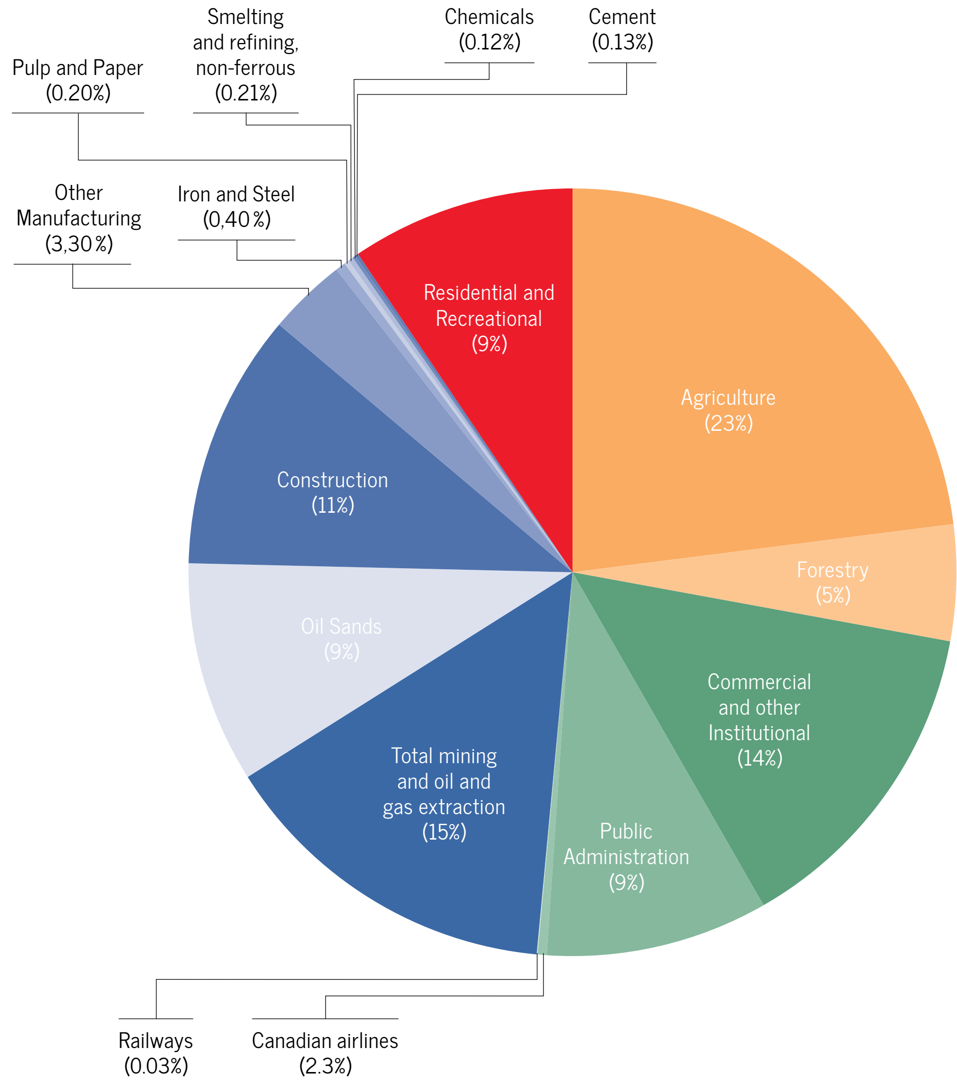
2.4 Energy use breakdown

Since the database used to build the profiles was designed primarily for emissions reporting purposes, the data and shares presented below are limited to equipment that uses GHG-emitting energy sources. These sources include biodiesel, diesel fuel oil, ethanol, lubricating oils and greases, motor gasoline, natural gas, and propane.

Within the entire IPCC off-road transport category, a total of 661 TJ of energy from emitting sources was used in 2022. This energy derived mainly from diesel (72.3%) and gasoline (23.4%).

When the fuel mix within each of the IPCC sub-categories for off-road transport is broken down, diesel dominates more strongly in manufacturing, mining and construction (90.0% for 2022), and agriculture and forestry (96.8%), while gasoline is more significant in the commercial and institutional (46.5%), residential (95.8%) and other transportation (83.7%) categories.

Figure 2 – Off-road emissions by economic sector (2022)



3. Challenges and opportunities across sectors

This section presents information gathered from a review of institutional and academic literature on off-road decarbonization, supported by conversations during recent IET work with experts in the field involved in the decarbonization of off-road vehicles and machinery. The review focuses on decarbonization options in general as well as on the specific issue of electricity-based technologies. The following descriptions are not intended to be exhaustive but rather to present several key off-road transport trends and ideas relating to the most pressing questions facing organizations and governments attempting to decarbonize their operations or sectors altogether. Since most of the literature available examines non-Canadian context, the added contributions from exchanges with experts formed a basis for discussing parts or forms of these challenges in the more specific context of Canada's sectors.

The overview below attempts to answer the following questions:

- What is the potential for electricity-based technologies to decarbonize off-road in each sector?
- What is the commercial availability of the low-carbon equipment needed?
- How much of a change in practices would be required to adopt the decarbonized technologies or alternative, low-carbon operation modes?
- How dependent is Canada on foreign actors for these decarbonization efforts?
- Overall, what are some of the key challenges of implementing solutions to decarbonize off-road in the sector?

3.1 Mining and oil and gas extraction

Prospects for the decarbonization of underground mining activities have changed dramatically in the last two years or so, during which time a cementing of electrification's leading role seems to be taking hold. In addition to the decline in battery costs in recent months and years (Ranggård and Öhmark 2024), the operation of underground mining sites makes electricity an interesting option for several reasons. First, electricity distribution infrastructure within the site and electricity transmission infrastructure to the site are often already in place and would require relatively modest upgrades to allow for the operation of electric vehicles. Since a large part of underground mining is already electrified across Canada, further electrifying vehicles and machinery more specifically pertains to vehicle options. Installation of charging equipment is relatively straightforward and battery swapping systems make it less demanding in terms of logistics.

Second, the use of electric machinery and vehicles reduces ventilation needs for underground sites given the absence of pollutant emissions, which in turn sharply reduces electricity demand for such ventilation and the associated costs. This then makes the cost premium of electrification much lower than the simple additional cost of electric vehicles (IGO, Perenti & ABB 2024). The result is a more manageable increase in power demand for the site, given the large quantity of electrical machinery already in place.

The perspectives for decarbonizing open-pit mining are quite different owing to various constraints and needs. Since there is no advantage tied to reduced ventilation needs, the cost of batteries and battery-electric vehicles makes the electrification premium much higher than in underground mining. Alternative solutions like catenary lines also pose challenges, given the unpaved roads, making vertical stability—and in turn, reliability—a concern. Generally, since the extraction site changes and moves over time, refueling or recharging infrastructure must be relatively mobile.

Some OEMs are deploying solutions to these challenges. One example is Caterpillar's dynamic energy transfer system, which charges vehicles while they are rolling with the help of a small side catenary. Since the system requires less stability and uses smaller posts driven less deeply into the ground, its infrastructure can be more easily moved every few years.

More generally, although several manufacturers already offer electric models for large equipment, most larger producers are global manufacturers located outside of Canada, such as Caterpillar and Sanvic. There are some Canadian OEMs but they are currently smaller in size (MacLean Engineering, for instance).

Key points:

- Mining operational requirements for off-road equipment are constraining since operations are often continuous for 24 hours a day and seven days a week.
- While electrifying vehicles is harder than electrifying other equipment, the underground mining context reduces both the cost and the logistical challenges of their electrification; the possibility of installing battery swapping stations in various locations in the mine also makes hybrid powertrains (instead of fully electric systems) unnecessary.
- Electrification offers several additional benefits to underground mining, including reduced health concerns tied to emissions and noise; quantified cost analyses can also help demonstrate the value of the switch to mining companies that are still hesitating.
- Since decarbonization efforts are at an earlier stage in surface mining, no dominant technology is as yet available for vehicles;
- Although limited information was gathered in this report for oil and gas operations, conditions may differ from those applicable to other types of open-pit operations and warrant an in-depth and tailored analysis, especially as it constitutes a very large portion of off-road emissions for this sector

3.2 Commercial, public administration and other institutional

Commercial, public administration and other institutional operations embrace a broad variety of equipment and vehicles for off-road services. As in other sectors, the decarbonization challenge for many vehicles is first and foremost linked to operating conditions. At the municipal level, for instance, the prospects and trends for the electrification of landscaping (for buildings and parks) are developing rapidly, with available equipment and longer battery lives for even larger machinery more readily accessible. In contrast, operations requiring heavy-duty vehicles for tasks like snow removal suffer from the unavailability of electric vehicles. Although snowplowing vehicles are more available, logistical challenges posed by the duration of operations (almost continuous during the day for several days in a row, in some cases) remain. Local manufacturers and charging equipment OEMs are also rare.

In public administration, public security concerns also constrain decarbonization efforts, especially when considering the full electrification of vehicles. Snow removal operations, for instance, not only involve continuous operations needs that are sometimes hard to predict, but vehicles and equipment must also be ready for use at any moment. The inability to meet these requirements implies risks for the public in terms of the safe use of the road transport network. In this context, battery swapping and very fast charging seem unavoidable. This challenge is similar to operating conditions for public transport, where resilience requirements are well above those of other services provided by the grid, making contingency plans in the case of a blackout a necessity.

The decarbonization of off-road transport in public administration also involves addressing public works needs. Some options are now available for electricity-powered small equipment, such as bucket trucks, backhoes and mini-loaders. Batteries also partially fulfil the counterweight need for some of these vehicles. The city of Toronto has also partnered with Mack to develop an electric garbage truck and with Siemens for adapted charging stations.

A North American trend is currently developing in which large and medium-sized cities are frequently and repeatedly exchanging test results and experiences. This dynamic includes the C40 global network of cities, where New York City, for instance, has proposed a strategy for off-road decarbonization.

Most city-level heavy-duty vehicles are manufactured outside of Canada, although some accessories (buckets for dump trucks, for example) are locally available. Local manufacturers of electric city buses remain limited as well, especially after the bankruptcy of Lion Electric in Quebec.

Key points:

- While the electrification of off-road needs in the commercial and institutional sector is possible, it is complicated by the very broad variety of vehicles and equipment; helping operators by building a catalogue of what is available, including charging equipment options with the participation of utilities, is necessary on the very short term.
- The above also holds true for public administration, which has already seen some limited electrification of relatively small construction vehicles; however, because the services provided by public authorities often involve much higher resilience requirements for public security purposes, careful resiliency planning is needed to accompany the decarbonization of this equipment.
- Pooling resources by using existing city-level collaborations to foster testing and model development is important on the short term, especially for larger vehicles where options are currently more limited.
- Limited information on the status of decarbonization efforts was available for the commercial sector, apart from the fact that, similarly to manufacturing industries, a large part of the off-road needs is for forklifts; significant noise reduction co-benefits, especially indoors, were also noted.

3.3 Construction

Attempts at decarbonizing off-road transport in construction applications have so far been extremely limited and remain largely state-level or municipal initiatives. For instance, zero-emission construction zones are being planned in Toronto, similarly to those being planned in California, Norway and Finland, or more recently, New York City.

So far, no single manufacturer of off-road construction machinery stands out globally. Most models are largely developed in partnership with cities for specific applications and conditions of operation (see above discussion for public administration). In any event, according to the information gathered for this report, no Canadian manufacturer has deployed electric models or developed mobile charging equipment that could accommodate the temporary nature of most construction sites.

One important challenge for the decarbonization of construction off-road equipment is the size and temporary nature of construction sites. Short-lived sites, for instance, may not have easy access to electricity supply (due to lack of space or to the fixed costs associated with it). This challenge should not be overstated however: larger sites are typically longer term and generally have more space for additional equipment like battery swapping stations or temporary chargers; direct connexions to the grid also present a lower added cost in relative terms. The latter is partly because construction sites are also typically situated within grid reach, especially in urban areas, making additional power needs manageable. As a result, an approach to streamline connection for short-term sites could be developed.

Finally, although a vast number of types of equipment are used in construction, only a handful are responsible for a large share of total emissions, which allows for a targeted approach.

Key points:

- Challenges to electrification tied to operational requirements in construction depend on site conditions more than on vehicle type: smaller, short-term sites like single-home renovations may benefit from streamlining that allows for rapid, low-cost and short-term connection to the grid for needs on site; needs are also typically for smaller equipment than those of larger sites.
- Greater low-carbon equipment availability is currently very limited for larger sites; the building of a catalogue of models for private actors and the establishment of test sites and projects should be a priority to determine how to best proceed over time.
- In all cases, hours of operation are typically shorter, allowing the flexibility needed for charging, in addition to providing noise reduction benefits in inhabited areas and air quality benefits for workers.

3.4 Forestry

Vehicle and machinery emissions constitute a significant share of forestry's GHG footprint, although the off-road share of this transport is smaller than the on-road share. Most decarbonization efforts so far have been focused on improving the logistics of transport and/or increasing the use of biofuels, with relatively limited impacts on greenhouse gas emissions. More recently, some initiatives have examined the possibility of electrifying long-haul log transport, with or without the aid of route optimization software that can enable transport fleets to take advantage of terrain topology and use regenerative breaking technology to charge batteries on loaded trucks as they proceed downhill from the logging site (after climbing uphill empty, which requires less energy from the onboard battery). For example, Resolute Forest Products is developing an electrified planetary truck with a partner in Quebec for one of its forestry roads where the proximity of renewable electricity infrastructure can help with charging installations along the road. In addition, FPInnovations is testing a hybrid trailer; some firms are looking into autonomous vehicles; and other electric or hybrid heavy-duty trucks are being developed, some by Canadian startups like Edison Motors.

While some of this transport occurs on-road, one challenge that further complicates efforts to decarbonize the off-road segment is that the rest of the (on-site) equipment cannot take advantage of the more favourable conditions of forestry roads used to carry logs from the forest to the sawmills. Once vehicles leave these roads, the terrain is unpaved, making powering and operating charging equipment much more complicated. While mobile hydrogen refueling stations could potentially be helpful, their availability for testing is currently limited. Although some Finnish and Swedish companies produce electric harvesters, their unavailability in Canada and the lack of grid access in many harvesting regions has limited their testing and deployment. Equipment is also left on-site for weeks, complicating recharge opportunities.

Key points:

- Access to low-carbon equipment like harvesters is complicated by supply chain constraints and model availability limitations.
- A one-size-fits-all decarbonization strategy for off-road forestry needs would not be advisable: a roadmap with options dependent on categories of site conditions could be quickly developed to start testing equipment in different conditions.

3.5 Agriculture

While information gathered for off-road options in the agriculture sector was more limited, the challenges to decarbonization are well known. The significant infrastructure needs to distribute electricity or low-carbon fuels to agricultural sites, the range of vehicles and hours of operations, and more generally the cost of existing low-carbon equipment, remain significant constraints which contribute to a reluctance for large-scale transformations to vehicle fleets.

Key points:

- Like in the forestry industry, the decarbonization options for large vehicles and equipment in the agricultural sector largely depend on the location of the sites and the surrounding areas: where grid capacity is nearby, additional infrastructure to provide power needs for charging is more economical and should be explored; in more remote areas or where grid capacity is constrained, a more comprehensive assessment of available options is necessary, one of which is sustainable liquid fuels that could be produced locally with residues.
- Since no information on low-carbon equipment and vehicle availability was obtained during this project, further study is needed to assess the options available to the sector.
- The long hours of vehicle operation during consecutive days in key periods over the course of the year, in combination with long distances to base, add to the logistical challenges facing electrified options (charging or battery swapping).

3.6 Residential and recreational

Residential and recreational equipment is very diverse, although a large share of it is small scale and already benefiting from electric options (snowblowers, lawnmowers, four-wheelers, etc.). The decarbonization of recreational vehicles often brings the added problems associated with geographical isolation (no grid availability in remote regions, for instance) and user habits.

Key points:

- The availability of electrical equipment for residential off-road services, combined with the negligible additional power needs or hours of operation, makes it possible to rapidly decarbonize with the proper regulations and/or incentives; reduced local noise and air pollution add to the benefits of such a transformation.
- The decarbonization of recreational equipment requires a closer look given that barriers linked to personal habits and complexities specific to remote locations (including a need for long range in cold weather) remain.

4. Conclusion

By combining these insights, it is possible to identify a number of cross-cutting issues in the design of policies for decarbonizing off-road transport in the Canadian context. A first challenge is whether a non-emitting **replacement technology** providing workable conditions for the service offered is **readily available**. Most of the manufacturing of certain types of equipment, especially heavy-duty machinery and vehicles, takes place outside of Canada, which can imply having to rely on complex supply chains and facing delays in obtaining the equipment, as well as having to ensure that the equipment complies with Canadian regulations. These constraints are in addition to the arduous task of determining model availability for smaller actors like small business operators and municipal fleet coordinators.

In addition to supply chain issues, the use of non-emitting equipment often involves **additional constraints and requirements**, such as range and charging time for electricity-powered equipment replacing diesel engines. The need to ensure a certain minimal operation time for some equipment creates at best an added logistical constraint for users where long and frequent charging times must be carefully planned. At worst, it requires the doubling of equipment, with the ensuing upward pressure on the transformation cost.

As well as the previous challenge, in many cases **alternative energy sources** to propel off-road equipment require **significant additional infrastructure**, which may be necessary to provide sufficient power for charging equipment and vehicles or to distribute alternative fuels like biofuels or hydrogen for non-electric equipment. Moreover, some of the infrastructure must allow for frequent moving or retirement, such as in construction sites or open-pit mining.

In light of all the above, an essential starting point to developing a strategic approach to the decarbonization of off-road transport is to build a comparative assessment of these challenges, their importance for specific off-road services, the opportunities in some Canadian contexts, and the benefits of each option beyond the reduction of GHG emissions and contribution to a net-zero pathway for Canada. Table 3 provides an example of such a grid.[7]

Table 3 – Assessment grid for decarbonization solutions

Sector	Example application/ technology	Technology/ model availability	Needs for new infrastructure or modifications	Induced security impact/resilience requirements	Noise reduction benefit	Other pollutant reduction benefit
Agriculture	BEV[8] on-farm tractors (small to medium size)	Some models available but limited deployment	Substantial, especially for remote areas	Long hours and continuous days of operation during crunch periods	Unlikely to be determinant	Important from the replacement of diesel
Mining	BEV underground haulers	Available but limited deployment	Substantial in terms of charging equipment but additional power needs typically low for sites that are already electrified	Not negligible but some flexibility available in typical sites	High	Reduced need for ventilation underground
Construction	BEV large equipment on site in urban settings	Some models available but limited deployment	Several options to deploy charging, including direct grid connection	Hours of operation may allow for smaller logistical changes due to charging needs	High, especially in existing residential neighbourhoods, although noise remains substantial during operation	High
Public administration	BEV municipal garbage collection	Some models available from partnerships	Important, necessitate careful logistical planning of charging sites	Important, but predictable	Very high	High
Residential	Electrified lawn equipment	High	Accommodated by existing installations	None	Not negligible, but noise remains substantial during operation	High, including the elimination of the need to store petroleum products

[7] This grid was developed by adapting the approach set out in Meadowcroft and contributors (2021), where a similar assessment of various decarbonization options across sectors is summarized in similar colour-coded tables.
[8] Battery-electric vehicle.

Since cost impacts are complex across applications, they are not included in Table 3, even though they would be a key consideration for stakeholders involved in decarbonization efforts, as discussed in the previous section. Otherwise, the grid proposed should be understood as follows:

- Each row is a potential service decarbonization option: it is then accompanied by a colour-coded perspective on five dimensions.
- The first dimension refers to the level of availability of the technology in the current state of markets in Canada, for instance whether several models are known and already deployed.
- The second dimension speaks to the need for additional energy production, transport and distribution infrastructure that would be required for the decarbonization option to be implemented.
- The third dimension pertains to the security challenges that may be associated with the option, which may require difficult considerations for resilience (for instance, if an electricity outage creates an additional public security risk due to BEVs having replaced fuel-based vehicles).
- The fourth option addresses the specific co-benefit of noise reduction, which may be of particular relevance in indoor, enclosed and/or populated environments.
- The fifth option relates to additional pollution reduction benefits and their importance in the given context of the service: for instance, replacing diesel with electric engines reduces pollutant emissions beyond GHGs, although this benefit is of greater importance in indoor environments and in general where health concerns due to these pollutants is higher.

The proposed colour code shows green when the transformation would have a positive result on the column's criteria (with light or dark variation to show the importance of the positive change), yellow when there are some hints or developments that suggest it could be positive but not without significant advancement or specific conditions; and red if the impact of the change for the given criteria would be negative—in other words it creates concerns.

The grid contains just a few examples for illustration purposes. The first step of a next phase would be to expand this grid for as many services as possible across sectors. For instance, this could be achieved through consultation with key actors and stakeholders in each sector after exploring the state of the land, based on their experience. Criteria of additional importance could also be added.

Once a more comprehensive grid has been developed, **we propose to design the strategic approach using a stepwise learning process. Such an approach should prioritize immediate opportunities, designing targeted pilot projects in a way that maximizes learning opportunities for off-road activities, and identify areas where decarbonization pathways are most difficult in the short and medium term and where significant exploration will help clarify the needs.** The steps of this approach should follow four higher-level principles:

1) Maximize electrification where possible: of the different possible energy source switches, moving from diesel to electricity is the most compatible with net-zero objectives. Electrification should thus lead the first pass across options and sectors.

2) Explore other low-carbon energy sources based on potential co-benefits and nearby infrastructure availability. For instance, there are instances where the missing electricity infrastructure is significant or where electrification presents too many shortfalls. If biomass resources are readily available and will remain so in such an operation– for instance in agricultural operations with high rates of residues that could be transformed into sustainable liquid fuels—the true potential, costs and challenges of a derived solution put to scale should be rapidly mapped out.

3) Anticipate information gathering for technologies and share this information with relevant actors and stakeholders. Availability of technologies and models for specific services is sometimes hard to determine without large-scale coordination of efforts by stakeholders, making it difficult to design transformation plans. Filling this gap and making the information widely available could speed up transformations.

4) Launch pilot projects to test options. Based on the assessment grid and on the three above criteria, pilots should be chosen and designed to maximize the potential for learning and to spill over into other sectors where decarbonization options face similar challenges. For instance, testing heavy duty BEVs in mining sites where vehicles are operated for long hours and consecutive days in a circumscribed geographical area could help gather useful information not only for similar sites elsewhere, but even for municipalities considering a move to BEVs for their own long-hour and consecutive day operations (snow removal operations, for instance). Learning lessons from the former's experience with the logistics of such a transformation, where security concerns are different than for snow removal, for example, could be helpful for municipal planners, in addition to learning from pilots done in other jurisdictions in more comparable settings. Planning pilot projects with this in mind would maximize the benefits even beyond the area of operation of a specific test project.

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