Renewable Energy 217 (2023) 119178

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Decarbonizing Canada's energy supply and exports with solar PV and e-fuels

Carly Bennett [a,*], Jocelyn Blanchet [a], Keena Trowell [b], Jeffrey Bergthorson [a]

[a] Alternative Fuels Laboratory, Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montréal, Canada
[b] Department of Mechanical Engineering, McMaster University, 1280 Main Street West, Hamilton, Canada

ARTICLE INFO

*Keywords:*
Photovoltaic energy
E-fuels
Energy transition
Land use
Metal fuels
Power-to-X

ABSTRACT

Implementation of large-scale photovoltaic (PV) and e-fuels in Canada could help mitigate GHG emissions while also producing enough energy to meet demand. This study examines the potential of PV electricity to meet Canada's energy demand at three levels: replacement of GHG-emitting electricity, replacement of GHG-emitting secondary energy use, and replacement of fossil fuel exports. Secondary energy is replaced with direct electrification and e-fuels created using solar electricity. Energy exports are in the form of e-fuels, produced using solar energy. The amount of land and increased electricity generation needed is calculated.

If Canada were to simply decarbonize its grid, an equivalent of only 7.3% of the land currently used in oil and gas production in Alberta would be needed for PV panels. To replace both electricity and GHG-emitting secondary energy uses, Canada would need a 4.7- to 7.7-fold increase in its current clean electricity generation. To completely decarbonize all domestic energy, and maintain current levels of energy exports, Canada would need to increase its current clean electrical generation by 13.4 to 16.5 times. PV panels would cover less than 1.6% of Canada's land mass.

## 1. Introduction

Anthropogenic climate change contributes to more frequent droughts, wildfires, acidification of the oceans, melting of glaciers and ice caps, rising ocean levels, and extreme weather events. Reducing greenhouse gas (GHG) emissions by curbing the use of fossil fuels is needed in order to mitigate climate change.

While the oil and gas industry has been historically important for Canada's economy, it is also responsible for 11% of the country's GHG emissions [1]. It has provided well-paying jobs [2], with Alberta's oil and gas sector providing 140,300 jobs in 2017 [3], and contributed 6% to Canada's GDP in 2020 [4,5]. To transition Canada's economy away from fossil fuels, a suitable replacement is required. This replacement would need to provide energy and high-quality jobs while contributing to a sustainable future.

Oil prices plummeted in 2020, reaching their lowest level since 1986 [6], due to overproduction and saturated storage facilities. This caused many oil sand projects in Northern Alberta to be canceled [7]. In April 2020, Athabasca Oil Corp. suspended some *in-situ* mining projects, causing a 15% decrease in employment in the area [8]. The volatility of the oil market makes investment in a cleaner energy landscape a safer way forward for the jobs of Canadians.

Renewable sources of energy are becoming a more economic investment option. The unsubsidized levelized cost of electricity (LCOE) for renewables has been steadily decreasing, with wind- and solar-powered electricity now being less expensive to produce than electricity powered by coal, nuclear, or natural gas [9]. Solar has had the most dramatic drop in average LCOE: an 85% decrease from 2010 to 2020. The global LCOE average for newly commissioned utility-scale solar projects went from 38¢/kWh to 5.7¢/kWh [10] during that time period. The affordability of solar photovoltaic (PV) energy is largely due to rapidly decreasing installation prices. Between 2010 and 2019, installation prices fell from \$4702/kW to \$995/kW [11]. The energy return on investment (EROI) for PV technology ranges from 20 to 21 and the energy payback time (EPBT) ranges from 1.3 to 1.5 years, even for regions with low insolation levels like Canada [12].

In addition, for every TWh of solar electricity produced, 900 job-years are created, which is 8 times more than the job-years created per TWh of natural gas-, coal-, or nuclear-powered electricity and over 4 times the number of job-years created per TWh of other renewables, like hydro and wind [13]. For each direct job in the solar industry, about 1.8 indirect jobs are created in supporting industries [14]. Furthermore, fossil energy sources are a diminishing reserve while solar energy can sustainably contribute to the Canadian economy as long as PV arrays are installed. PV energy would provide more jobs in the Canadian energy sector, while simultaneously decarbonizing it.

Previous work has shown that renewables are able to produce enough energy to decarbonize the energy sector [15–17]. However,

* Corresponding author.
*E-mail address:* carly.bennett@mail.mcgill.ca (C. Bennett).

https://doi.org/10.1016/j.renene.2023.119178
Received 18 March 2022; Received in revised form 17 July 2023; Accepted 11 August 2023
Available online 14 August 2023

implementing variable renewable energy systems for the deep decarbonization of electricity grids raises significant operational challenges for grid stability and reliability [18]. We recognize that a decarbonized energy system would rely on a mix of sources, including hydro, wind, geothermal, and nuclear. The goal of this paper is not to suggest that the proposed path is the optimal one, but rather to chart, at a high level, the energy required to decarbonize Canada's energy system. On a similar note, this paper does not consider the cost or investment needed to implement said option which include the construction of additional electricity transportation lines, nor any grid stability infrastructure related to high penetration of non-dispatchable renewables amongst others.

One study focused on global decarbonization and assumed an annual energy demand of 148,000 TWh in 2030, if no further decarbonization efforts were made [15,16]. It analyzed the technologies needed to replace the current GHG-emitting technologies, suggesting direct electrification wherever possible, and hydrogen as an energy carrier everywhere else. Once the efficiencies of the replacing technologies were considered, this study found that the end-use energy, which is directly consumed by the users, would decrease by 30% when replaced with wind-, water-, and solar-powered electricity [15].

Another study focused on the decarbonization of Canada's secondary energy use [17]. Secondary energy is the net energy after conversion into a transportable form [19]. It found that Canada has the resources and land necessary to provide 3750 TWh of energy using a mix of renewable energy sources, with a special emphasis on wind. However, the study did not take into consideration the efficiency losses of the technologies needed to replace the use of fossil fuels, nor the energy currently exported from Canada to power other countries.

Seasonal variability and energy storage pose challenges to the widespread adoption of solar and other renewables. Long duration storage can mitigate the impact of the variability in the availability of solar energy at different times of the year by allowing the excess solar energy available in the summer months to be stored for use in the winter months. E-fuels and pumped-hydro storage are proposed as a way to store energy on a seasonal basis. E-fuels are energy carriers, like hydrogen, ammonia and synthetic hydrocarbons, produced with clean electricity via carbon-neutral processes. E-fuels also provide a way to export solar energy in the form of a renewable-energy commodity, providing a pathway for export and trade of sustainable energy.

It has also been shown that some curtailment is required to achieve the lowest overall LCOE for variable energy sources [20]. This implies overbuilding the power generation capacity so that the energy demand is met even when the variable energy sources are producing less than expected. Curtailment reduces LCOE by reducing the need for long term storage but it increases the land area required to meet the demand. This poses challenges for countries with high population densities. This paper aims to minimize the land required to produce enough electricity through solar photovoltaic cells. Therefore, no curtailment is allowed.

In this study, we examine the complete decarbonization of Canada's entire energy sector, including energy exports, using solar PV plants installed on marginal land and previously disturbed sites, starting with the Cold Lake region in Alberta. The associated land area required to create the solar PV farms in Canada is also examined. Rather than creating new land use changes, the implementation of renewable energy operations on previously disturbed industrial sites is encouraged by Government of Alberta policy [21]. Use of marginal land in Alberta for implementation of renewable energy is already in the works, with the RenuWell Project converting abandoned oil wells into PV projects in Taber, Alberta [22], showing the feasibility of the proposed energy transition.

We recognize that power generation would likely be spread across Canada and comprised of a mix of renewable energy sources including wind, nuclear, and geothermal. But, solar PV was chosen to be the focus of this study over other renewable energy sources such as wind, hydro, and geothermal because it represents the worst case scenario in terms of land usage. While wind turbines would also require a large amount of land, the actual foot print of the wind turbines is small such that they can easily be combined with agricultural crops. Solar PV panels can also be combined with shade tolerant crops [23] but is unlikely to scale to the size described in this study since it is economical only for certain crops.

In 2017, Canadians consumed 2574 TWh and exported, in the form of crude oil, natural gas and coal, 3131 TWh of energy [24–26]. 82.9%, or 2045 TWh, of the energy used by consumers, came from the direct combustion of fossil fuels while the remaining 17.1% came in the form of electricity [27]. 18% of Canada's electricity generation, or 120 TWh, came from combustion of hydrocarbon fuels in 2017 [27]. In this study, direct electrification is prioritized and, where this is not possible, e-fuels produced from solar power are proposed. We examine the land needed and job-years created for three scenarios:

(i) Decarbonizing the remaining 18%, or 120 TWh, of Canada's electricity grid;
(ii) Decarbonizing secondary energy use in Canada;
(iii) Matching current energy exports with clean fuel exports produced by renewable electricity.

## 2. Methods

### 2.1. Decarbonizing Canada's electricity grid

Though most of Canada's electricity comes from renewable sources, approximately 9% comes from the combustion of coal and another 9% from the combustion of natural gas and petroleum. This section addresses the land required to replace this fossil-fueled electricity with a PV plant in Cold Lake, Alberta.

The insolation used to compute the power density for solar panels was calculated for the land occupied by Cold Lake oil sands projects. This value was then extrapolated to the rest of the marginal land in the Canadian landscape as most of the marginal land favorable to solar projects falls in areas with better insolation characteristics with only a few areas in British Columbia being a bit lower. The data came from a standard Geographical Information System (GIS) software and 2006 data from Natural Resources Canada (NRCAN) [28]. The GIS data is produced from 144 meteorological stations across Canada. This study uses the latitude minus 15° (LM15) tilt orientation as this is near optimal for fixed-axis solar panels to collect incoming solar radiation.

For each month, the mean daily insolation (MMDI, kWh/m$^2$) is found by clipping the LM15 to the boundaries of the *in-situ* mining projects found in the Cold Lake region. The mean monthly insolation (MMI) is found by multiplying the MMDI by the number of days in each month. From the MMI, we calculate the monthly PV potential (MPVP, kWh/m$^2$) to determine the amount of electricity that could be produced by a region using Eq. (1).

$$\begin{aligned} \mathrm{MPVP} &= \mathrm{MMI} \times \mathrm{PR} \times \eta \times \mathrm{PF} \times \mathrm{GSR} \\ &= \mathrm{MMI} \times 0.80 \times 0.18 \times 0.31 \times 0.8 \\ &= \mathrm{MMI} \times 0.036 \end{aligned} \tag{1}$$

This calculation considers performance ratio (PR), the efficiency ($\eta$) of the solar cells, the packing factor (PF), and the generator-to-system ratio (GSR). The performance ratio is the comparison of the PV system yield to the peak system yield at ideal conditions. The solar panel efficiency represents the amount of electricity that can be derived from the insolation. We assume a constant performance ratio of 0.80 [29] and a solar panel efficiency of 18% [30], both values being standard for current technology. The packing factor is the ratio of the area of the solar panels over the area of the solar panels including the space between them to avoid excessive shading [31]. The total area including the space in between the panels is known as the generator area. This value is dependent on the angle of the solar panels and the latitude which yields in this case a PF of 0.31. The GSR, taken in Eq. (1) as 0.8, represents the ratio of generator area to the total area of the solar project which can also include access roads, substations, and other infrastructure required to operate the solar farm.

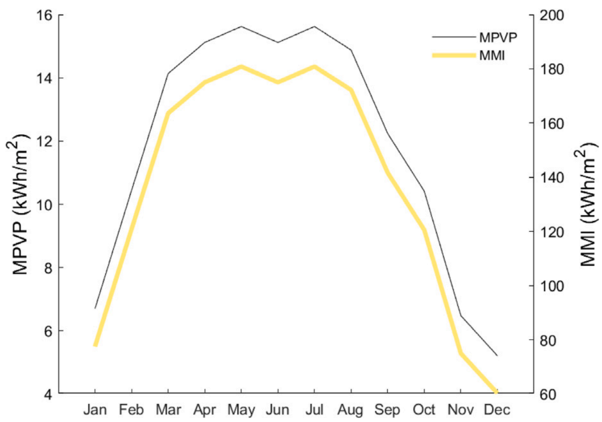


**Fig. 1.** Plot of mean monthly insolation and monthly PV potential per square meter within the *in-situ* project boundaries in the Cold Lake oil sands region.

### 2.2. Stationary long-duration energy storage

Seasonal storage can be done using stationary, long-duration storage methods such as pumped hydro and e-fuels. Pumped hydro storage uses excess electricity, whenever it is available, to pump water to an elevated reservoir. When the stored energy is needed, the water is released to generate electricity via turbines. This technology can store energy on the order of months with a high cycle efficiency of approximately 80% [32]. However, the implementation of pumped hydro storage is highly dependent on the local geography. It is likely that the best scenario in a fully decarbonized economy will be a mix of e-fuels, pumped hydro reservoirs and reservoirs filled with rain water. In this study, we assume that water reservoirs, both pumped and filled with rain water, spread across Canada will handle most the seasonal storage needs and that e-fuels will be used for the remaining. The average storage efficiency is taken as the pumped hydro storage efficiency of 80%.

### 2.3. E-fuels for secondary energy and energy trade

E-fuels offer more flexibility than pumped hydro as they can be transported and do not require specific topography. As shown in Fig. 1, there is a strong seasonal variability in solar energy. The colder months, October through February, require more energy due to heating demands. These colder months also happen to be the months with the least amount of insolation. When solar energy is at its peak, March through August, energy demand is at its lowest. To resolve this mismatch between production and demand, long duration energy storage is needed.

Energy carriers or e-fuels, the “X” in “Power-to-X”, can also be used to replace fossil fuels in applications that require transportation of energy. In a carbon-free energy system, energy carriers and storage need to be sustainable and to not emit any GHGs over their lifecycle. For this reason, we propose that these e-fuels be produced with the surplus solar electricity from March to September. Proposed e-fuels to aid in the decarbonization of Canada’s energy system include hydrogen, ammonia [33], synthetic hydrocarbons, and metal fuels [34–36]. The area of the solar field would need to be increased in order to accommodate the unavoidable thermodynamic losses associated with storing energy in e-fuels. This increase in area is determined by the power-to-X-to-power (p-X-p) efficiency of the energy vector, X. Higher efficiencies require lower increases in the size of the solar field.

Batteries are excluded for long-duration energy storage because of their poor performance in storing energy on the order of months [37]. Biofuels may also play a role as an energy carrier, but are omitted in this study due to the low productivity of photosynthesis per square meter [38] and the requirement of fertile land which would be diverted from growing food crops.

#### 2.3.1. Hydrogen

Hydrogen has a high specific energy and can be sustainably produced from renewable electricity and water. When oxidized through combustion in air, the products are heat and pure water, and when oxidized through a fuel cell, the products are electricity and water [39]. Hydrogen can play a role in both short-term storage, i.e. grid balancing, and the seasonal storage proposed here. A drawback of hydrogen is its low energy density. Even when stored as a cryogenic liquid, its energy density is only 1/3 that of gasoline. Compressing or liquefying hydrogen consumes 10% or 30%, respectively, of its energy content [40]. If liquefied hydrogen is used as the seasonal energy storage device, a p-X-p efficiency of approximately 20% is expected [35].

#### 2.3.2. Ammonia

Ammonia can be made using atmospheric nitrogen and hydrogen produced by electrolysis powered by renewable energy. The ammonia would store the clean energy at an efficiency of 42% [35]. The ammonia can then be stored and, when the energy is needed, “cracked”, to release the hydrogen. Ammonia offers an advantage over hydrogen in that it is more energy dense, but it has a lower specific energy and p-X-p efficiency. The p-X-p efficiency for ammonia is approximately 15% [35]. A higher efficiency of 18% is possible if the ammonia is combusted directly, but this approach carries the risk of nitrogen oxide ($NO_x$) formation. $NO_x$ emissions have a global warming potential (GWP) of 298 on a 100-year horizon, compared to $CO_2$’s GWP of 1 [41].

#### 2.3.3. Synthetic hydrocarbons

Synthetic hydrocarbons are carbon-based fuels, which use sequestered atmospheric $CO_2$ as a feedstock. The combustion of synthetic hydrocarbons produces $CO_2$. Carbon recycling helps minimize its accumulation in the atmosphere [42,43]. Renewable energy can be used in the direct air capture process to sequester the $CO_2$, and this energy can be stored in the bonds of a liquid fuel created by the Fischer–Tropsch process [42]. The power-to-X efficiency of this process is about 34% [42]. It is assumed that the synthetic hydrocarbons are drop-in fuels that directly replace conventional fossil fuels with the same X-to-power efficiency as the current technology, giving them a p-X-p efficiency of about 13% [44]. Because of this low p-X-p efficiency, the use of synthetic hydrocarbons is limited to cases where the other e-fuels are not a viable option, such as the aviation industry.

#### 2.3.4. Metal fuels

Metals can also be used to store energy. When oxidized in air, they release their stored energy as heat which can be used to power a heat engine [36]. Certain metals can also be oxidized with water to produce heat and hydrogen [45,46]. The oxides produced can be recycled [47–49], making them a sustainable energy carrier option [34–36,50]. The p-X-p efficiency of aluminum could be as high as 25% if the heat is used in an engine with 40% efficiency [35]. Using appropriate reduction techniques and clean energy would allow for these fuels to have a zero-carbon lifecycle.

For energy export purposes, metal fuels are a more practical energy vector than ammonia or hydrogen due to their high specific energy and energy density, ease of storage and transportation, and zero-loss of the stored energy [35]. Metals can be shipped to regions with an energy deficit, and traded on an energy market in the same way that is done with oil, coal, and natural gas today. The power-to-X efficiency of metals is 62% [35], and the X-to-power efficiencies, achieved at the point of application, is similar to those of the replaced fuels.

**Table 1**
Assumptions to obtain lower limit of electricity needed to replace Canadian secondary energy with photovoltaics.

| Secondary energy use | Breakdown | Fossil fuel energy in 2017[c] | Replacement | Replacement efficiency | Net energy ratio |
|---|---|---|---|---|---|
| *Residential* | Space/water heating | 240.7 | Heat pumps[a] | 2 | 0.5 |
| | Other | 2.5 | Direct electrification | 100% | 1.00 |
| *Commercial* | Space/water heating | 166.8 | Heat pumps[a] | 2 | 0.5 |
| | Other | 7.1 | Direct electrification | 100% | 1.00 |
| *Industry* | Can be electrified (44%) | 236.6 | Direct electrification | 100% | 1.00 |
| | Cannot be electrified (56%) | 561.8 | Hydrogen fuel | 67% | 1.49 |
| *Transportation* | Passenger | 315.6 | BEV[b] | 70% | 0.21 |
| | Freight | 320.2 | PEMFC[b] | 23% | 0.65 |
| | Aviation | 84.9 | Carbon-based e-fuel | 34% | 2.94 |
| | Off-road | 33.2 | BEV[b] | 70% | 0.21 |
| *Agriculture* | Non-motive | 17.4 | Direct electrification | 100% | 1.00 |
| | Motive | 58.1 | Ammonia fuel | 42% | 2.38 |

[a] Heat pumps are analyzed not by efficiency but by COP.

[b] Replacing ICEs that are 15% efficient; all others assumed to work at efficiencies similar to the replaced technology.

[c] In TWh.

### 2.4. Secondary energy replacement with e-fuels

In 2017, Canada consumed approximately 2574 TWh in secondary energy across five categories: residential, commercial/institutional, industrial, transportation and agricultural [51], as detailed in Table 1. Approximately 82.9% of this secondary energy is derived from fossil fuels [1]. In this section, we examine pathways to decarbonizing these sectors.

The upper limit of electricity generation represents a case where the fossil fuels used in all five secondary energy categories are replaced directly with e-fuels. We assume that the e-fuels would be produced from clean electricity, with an average electricity-to-fuel efficiency of 57%. This is based on the average efficiency of the production of hydrogen (67%), ammonia (42%), and aluminum (62%) [35]. As aviation only accounts for 3.4% of secondary energy [51], the production efficiency of synthetic hydrocarbons is omitted from this calculation. We assume that these e-fuels could be converted to heat or work at efficiencies similar to the existing fossil-fuel systems. The upper limit requires the most electricity production.

The lower limit electricity generation case is one where the fossil fuels are replaced with direct electricity wherever possible, and the balance is replaced with a zero-net-carbon e-fuel. The lower limit case requires the least amount of additional electricity generation. All assumptions used to obtain the lower limit of secondary energy are summarized in Table 1. In commercial/institutional and residential energy consumption, energy is used mainly for heating. We assume that the combustion of fossil fuels for heat would be replaced with a heat pump system, with an average coefficient of performance (COP) of 2 [52].

We base our estimate for energy use in the industrial sector on an analysis of industrial practices in Quebec, assuming that, based on the low electricity price in the province, maximum possible direct electrification has been reached. Direct electrification of industry in Quebec is approximately 44% [53]. The remaining 56% of industry is then assumed to be powered by hydrogen, produced at an efficiency of 67%.

The transportation sector can be further divided into four categories: passenger, off-road, freight, and aviation transport. Passenger and off-road vehicles, which currently use internal combustion engines (ICEs) at an efficiency of 15% [54], are replaced with battery electric vehicles (BEVs) with an electricity-to-work efficiency of 70% [55]. We assume that the ICEs currently used in freight transport are replaced with fuel cell electric vehicles (FCEVs), powered with hydrogen, with an electricity-to-work efficiency of 23% [56,57]. For aviation transport, we assume that the fossil fuels could be directly replaced by a drop-in liquid fuel produced from atmospheric $CO_2$ and solar electricity, at an electricity-to-fuel efficiency of 34% [42].

The agricultural energy sector is split into two categories: motive and non-motive energy use. In the agricultural context, non-motive energy use is primarily heating which could be fully electrified, with an assumed efficiency of 100%. Ammonia is a common agricultural input; therefore, farmers are already familiar with safe storing and handling procedures. Ammonia has been proposed to be used directly in internal combustion engines [58]. It has also been showed that ammonia storage in agricultural settings can help mitigate the intermittent nature of solar PV energy [59]. We assume ammonia directly replaces the fossil fuels used for motive applications without affecting the efficiency of the engines.

The last column of Table 1 shows the ratio of renewable energy needed to replace the fossil fuels currently used to provide the same amount of heat or work. This ratio takes into account the efficiency of the replacing technology, as well as the efficiency of the technology being replaced. In cases where this number is less than 1, the replacing technology is more efficient than the conventional, GHG-emitting, technology being replaced. In cases where this number is greater than 1, more primary energy is needed to replace the current technology, however this energy would come from renewables and, therefore, would be a sustainable way forward. Losses of energy are a thermodynamic reality in energy storage and in the conversion of electricity to e-fuels and the consumption of these fuels to produce work.

### 2.5. Land needed and job-years created for secondary energy use and energy exports

In this section, we find the land required to provide this secondary energy and energy exports with solar power. The amount of land needed for a solar farm to replace these cases is determined by assuming a uniform 54.6 kWh/m$^2$ (or 6.24 $W_{avg}/m^2$) annual PV potential using Eq. (1). The insolation was assumed to be 1530 kWh/m$^2$/year. This energy-per-area value is then used to find the area of solar panels needed to replace the different levels of secondary energy and energy exports with electricity.

An average of job-years created for each additional TWh of solar energy produced is 900 [13]. This includes jobs created by initial construction and installation, as well as maintenance and operation, which are averaged over the lifetime of the plant. This is likely a low estimate for the jobs created by the decarbonization of Canadian energy, as there would also be a number of jobs created in e-fuel plants.

### 2.6. Temporal analysis

Decarbonization of Canada's energy sector must occur by 2050 if Canada is to achieve its goal of net-zero emissions according to the

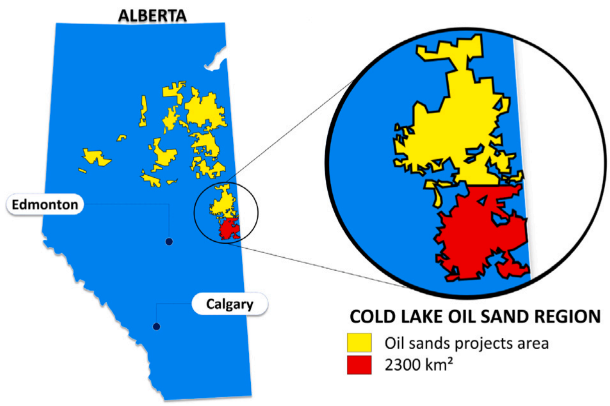


**Fig. 2.** Comparison of a 2300 km$^2$ solar farm sufficient to fully decarbonize Canada's remaining 120 TWh of electricity produced from fossil fuels compared to the oil sand projects in Alberta.

Canadian Net-Zero Emissions Accountability Act passed in November of 2020 [60]. The adoption and growth of new technologies are well-described by a logistic growth model as a function of time $t$ [61,62], as shown in Eq. (2):

$$f(t) = \frac{C}{1 + e^{-k(t-t_0)}} \tag{2}$$

with $C$ being the maximum value of electricity generation for each decarbonization pathway. The logistic growth constant, $k$, is calculated using the initial amount of solar (3.9 TWh in 2019 [63,64]), and final amount needed, $C$. In this instance, $k$ equals 0.3631. $t_0$ is the year that $f(t) = C/2$, or 2038.6. This equation models the new installed solar capacity each year, which is stacked on top of our current clean electricity generation.

To obtain the results of the temporal analysis, we assume that we reach 99% of our decarbonization goal by 2050, and that net energy use remains the same in 2050 as in 2018. While this paper suggests PV technology as a way forward for Canada's energy sector, a similar approach can be used to model the implementation of any other new sustainable energy sources (i.e. hydroelectric dams, wind turbines, geothermal, etc.) as well as a combination of them, which is the most likely scenario.

## 3. Results and discussion

### 3.1. Decarbonizing electricity in Canada

In order to decarbonize the remaining 18%, corresponding to 120 TWh, of Canada's current electricity consumption produced from fossil fuels, 2300 km$^2$ of solar farms producing 125 TWh of energy would be required. The extra energy produced by the solar farm compensates for the energy lost during the conversion and storage of the energy surpluses produced during the summer. Fig. 3 shows the seasonal variation in fossil-fueled electricity demand *vs* the potential of a 2300 km$^2$ solar farm. Grey and yellow shading indicates months that have a deficit and surplus of solar energy production, respectively. These monthly surpluses and deficits are the main challenge of decarbonizing electricity in Canada. The area of this solar farm is calculated to ensure that the annual surpluses, minus the losses to long-duration pumped hydro storage, would be equal to the annual deficits. In months that there is an energy surplus, roughly March to October, the excess energy would be stored in pumped hydro, which would then be used to generate electricity when demand exceeds supply, from November to February. About 24 TWh of surplus solar energy would be stored in long term stationary storage. These deficits could be further reduced by implementing a mixed renewable energy grid powered by both solar and wind. A PV farm of this magnitude would generate over 120,000 job-years.

Canada has 14,500 km$^2$ of built-up land [65]. Covering just 16% of this land in solar panels (ie roof tops) could provide enough energy to decarbonize the current electricity grid with virtually no land requirement. Canada also has 94,800 km$^2$ marginal land that cannot be used for agricultural purposes but still has sufficient insolation to allow for solar projects [66]. Most of this marginal land is concentrated in Alberta, Ontario, Manitoba and Saskatchewan [17]. Only 2.3% of this land is needed to produce enough electricity to phase out all fossil-fueled electricity generating power plants. For reference, if the farms were all concentrated in the Cold Lake region, the area needed for the projects would take up about one third of the current land currently used in oil and gas production in the Cold Lake region (6660 km$^2$) [67], or about 7.0% of all land currently used in oil and gas production for oil sand projects (31,500 km$^2$) [67] as shown in Fig. 2.

### 3.2. Decarbonizing secondary energy use in Canada

Secondary energy usage in Canada is the energy supplied after conversion into a usable form. It excludes the energy required to produce electricity or to refine oil and the energy exported out of the country. In 2017, secondary energy usage was 2574 TWh. 82.9% of the secondary energy use was provided by the combustion of fossil fuels. Under the assumption of direct electrification wherever possible and the balance being replaced with zero-net-carbon e-fuel, the Canadian energy sector would need to produce 2503 TWh of clean electricity. This equates to an increase of 1971 TWh, or a 4.7-fold increase, in carbon-free electricity production on top of 2017 levels. The breakdown of the secondary energy sectors is shown in Fig. 4. This figure shows how Canada's current secondary energy would look after the proposed decarbonization technologies outlined in Table 1. The different sectors of secondary energy are shown in their current state and after the proposed decarbonization. Arrows signify whether these replacements are more or less efficient than the current technology, with upward arrows signifying the latter. Approximately 36,100 km$^2$ of land would be needed for a solar farm to replace this lower limit of secondary energy. This represents 38.1% of the marginal land suitable for solar projects and is only 5.6% of the land used in Canada for agriculture [68] as shown in Fig. 5.

If current domestic fossil-fuel consumption was directly replaced with e-fuels, with no electrification, the Canadian grid would need to produce 4117 TWh, once the average efficiency of the recyclable fuels is factored in. This is considered as an upper limit of electricity needs as producing fuels require more energy than using fossil fuel due to thermodynamic losses associated with any energy conversion processes. This represents an increase in clean electricity of 3585 TWh per year, a 7.7-fold increase in current electricity production. The total land needed for a solar farm that would completely replace secondary energy use in Canada, for this upper limit of estimation, would be 65,600 km$^2$. For comparison, this represents 69.2% of the available marginal land and 10.2% of land used in Canada for agriculture [68]. The land needed for this upper limit of secondary energy use is shown in Fig. 5.

The actual solar electrical capacity and land needed to replace all secondary energy in Canada with solar power would fall somewhere between these lower and upper limits. This would mean that, based on the Canadian population in 2017, between 944 m$^2$ and 1715 m$^2$ of PV farm would be needed for each Canadian. For comparison, a Canadian's individual footprint for agriculture is 18,000 m$^2$ [68]. The number of job-years created by such a project would fall between 1.8 and 3.2 million.

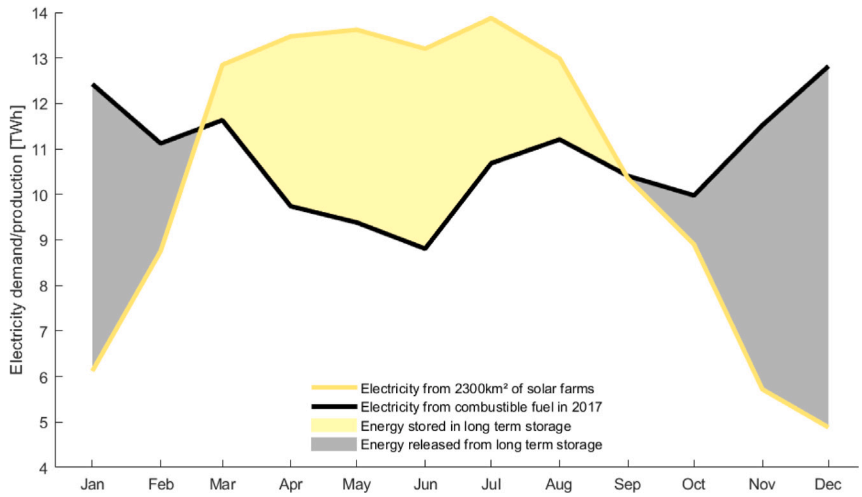


**Fig. 3.** Electricity derived from coal, oil and natural gas in 2017 compared to the potential electricity production from a 2300 square kilometer solar farm in the Cold Lake region on a monthly basis. Grey shading indicates the deficit in energy production during the winter months and the yellow shading shows the excess solar energy produced during the summer to compensate.

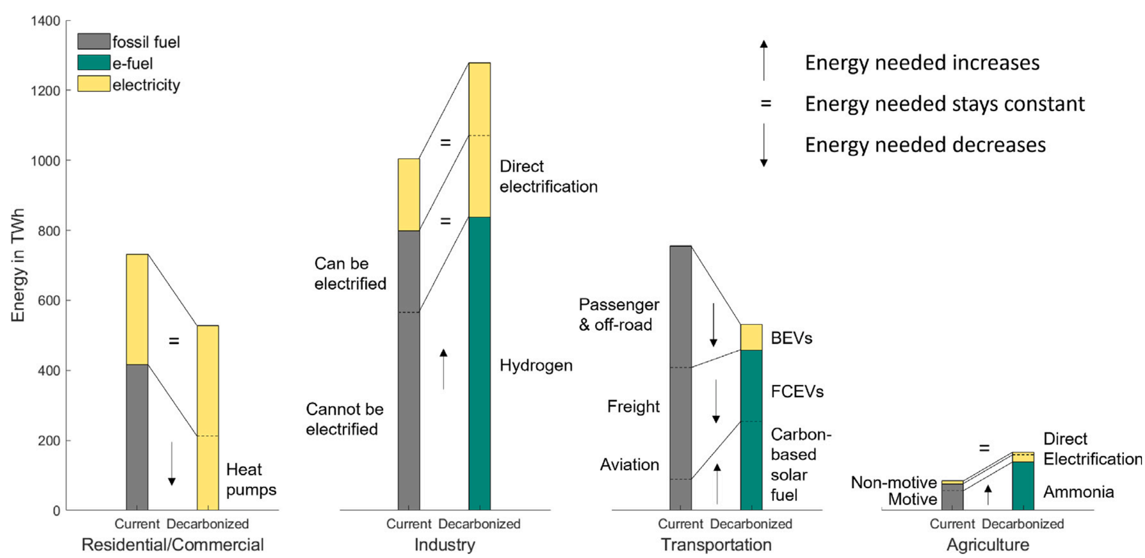


**Fig. 4.** Secondary energy use before and after proposed lower limit of decarbonization. Electricity currently used for each sector remains constant.

### *3.3. Decarbonizing energy exports from Canada*

In 2017, Canada exported 1.21 billion barrels of crude oil [24], 80.9 billion $m^3$ of natural gas [25], and 31 million tonnes of coal [26], which translates to about 3131 TWh of exported energy annually [69–71]. If energy exports are to be maintained at this level to ensure the continued prosperity of Canada, and to maintain Canada's role as an energy exporter, additional electrical generating capacity is needed, as are e-fuels, to store this electricity into commodities that can be traded on global markets. Of all the energy vectors discussed in this paper, aluminum is the most promising candidate for export purposes. It has a high energy density, requires no special considerations for storage or transportation, and Canada already possesses expertise in aluminum smelting [35].

To produce 3131 TWh of energy in the form of aluminum, 5050 TWh of electricity is needed, based on an electricity-to-fuel efficiency of 62% [35]. This would require approximately 92,400 $km^2$ of PV panels, which is nearly 1.4 times the amount of land needed to attain the upper limit of electricity to decarbonize secondary energy use. Fig. 5 shows the area added to the area already used to decarbonize the secondary energy usage in relation to marginal land. While this area is larger than the marginal land suitable for solar projects, it is important to point out that wind energy, both onshore and offshore, is another alternative to produce the clean energy required to transition away from a fossil fuel-based economy. Decarbonizing energy exports would create an additional 4.5 million job-years in the Canadian energy economy.

### *3.4. Temporal analysis*

Fig. 6 shows the amount of electricity required to decarbonize current electricity, secondary energy, and energy exports, as well as the fossil-fueled energy that the electricity would replace. Fig. 6(a) shows the lower limit of this analysis, with secondary energy demand being 2.8% lower when fossil fuels are replaced by the clean technologies outlined in Table 1. In the upper limit, shown in Fig. 6(b), secondary energy demand becomes 60% higher when fossil fuels are replaced directly with e-fuels. In both figures, energy exports require 61% more energy when replaced with metal fuels, and electricity requires the same amount as before decarbonization.

Fig. 6 also shows the logistic growth curves of the upper and lower limits of installed renewable electricity needed in order to reach full decarbonization. These curves are described using the average installation

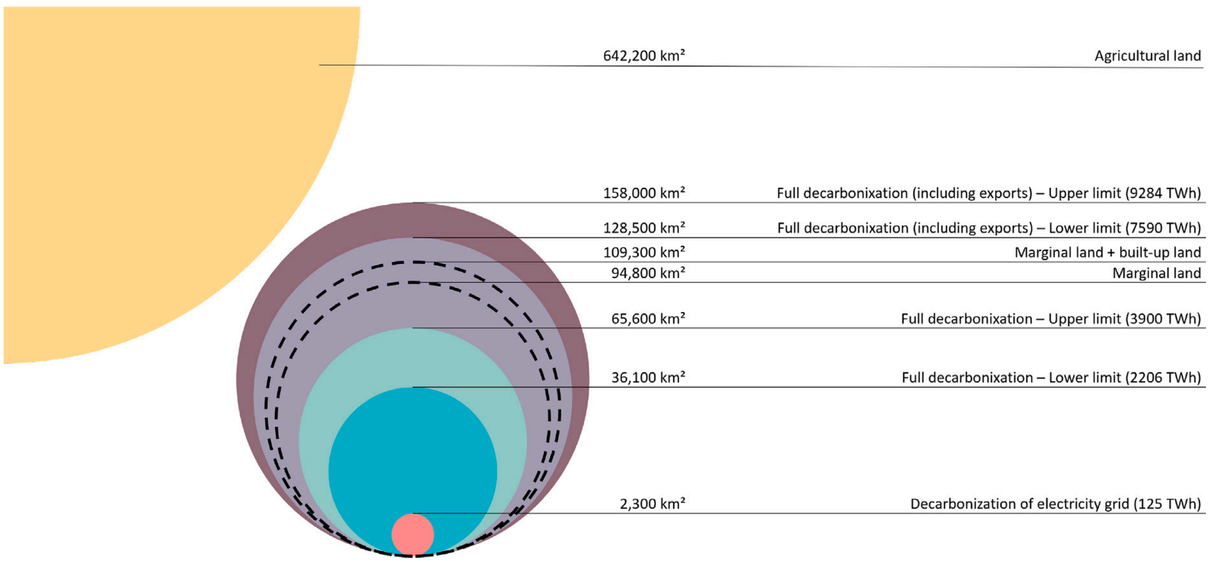


**Fig. 5.** The relative land needed to decarbonize all layers of Canada's energy system with PV solar farms. These layers of decarbonization are compared to the land needed for Canadian agriculture, the marginal land in Ontario, Manitoba, Saskatchewan and Alberta, as well as the land being used by oil sand companies in Alberta.

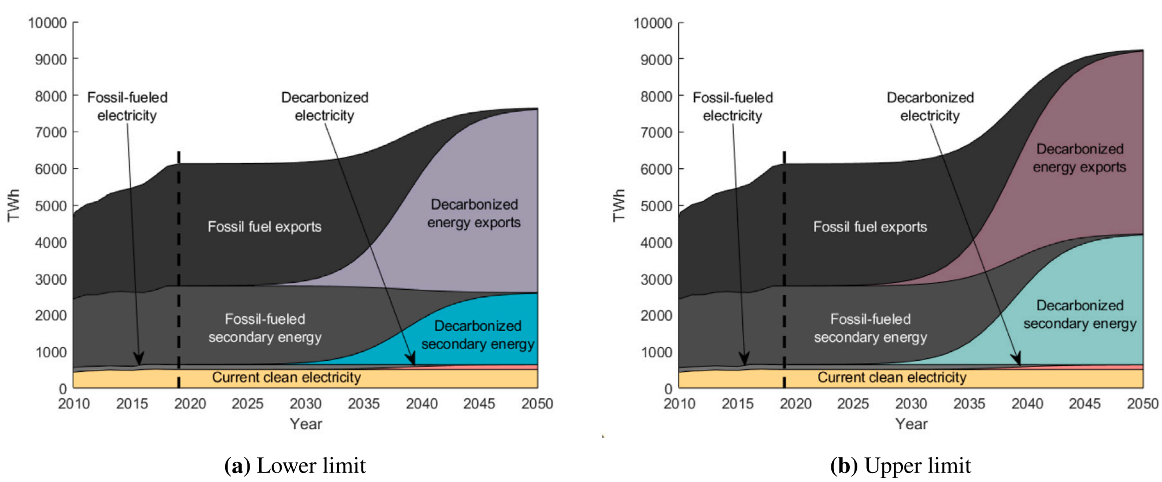


**Fig. 6.** Temporal analysis showing Canada's historical use and export of fossil fuels, as well as the transition needed to decarbonize electricity, the lower and upper limit of secondary energy (respectively), and energy exports by 2050. The amount of energy needed for secondary energy decreases for the lower limit and increases for the upper limit, the amount of energy needed for energy exports increases, and electricity stays the same. The dotted line represents where historical data ends and proposed transition begins.

rate needed between 2021 and 2050, as well as the maximum growth rate needed in the year 2038. To decarbonize electricity, an average installation of 4.0 TWh of solar electricity must be added per year, with the peak installation of 10.8 TWh/year. The relationship between yearly energy output and rated power is dependent on the insolation, which itself depends on location. However given the efficiency of the solar panels described in Eq. (1) and a mean insolation of 1530 kWh/m$^2$/year, this installation rate would be equivalent to an average of 3.3 GW per year with a maximum installation rate of 8.8 GW per year.

To decarbonize secondary energy use as well, this would require an average installation of solar electricity of 69.2–122 TWh (56.5–99.7 GW) per year, with maximum annual installation rate of 190–350.8 TWh (155–287 GW). Fig. 7 shows the growth needed to follow the pathway of decarbonizing just the lower limit of secondary energy use, with the breakdown separated into the sectors outlined in Table 1. Fig. 7 shows that decarbonizing Canadian industry, as well as aviation and residential heating, will be especially challenging for this proposed transition, due to the large amount of renewable energy growth needed for decarbonization. To decarbonize energy exports, on top of secondary energy and electricity, this would require an average annual installation of 236–289 TWh (193–236 GW) of new electricity, with maximum installation rate of 719–893 TWh (587–730 GW) per year. For reference, the global solar capacity was 600 GW producing 679 TWh of energy in 2019 [72]. This highlights the scale of the increase in clean energy needed to decarbonize Canada and, by extension, the world. While these growth rates are not due until 2038 if a logistic growth is followed, it will likely be a challenge for the supply chain to meet such a high demand for new solar capacity, especially as other countries also decarbonize their economy. It would still be a challenge even if other renewable energy sources, such as wind and tidal, were included.

From 2005 to 2015, Canada saw an average growth rate of 0.3 TWh per year [73]. The current action plan in place states that Canada will have 90% decarbonized electricity by 2030 [74]. The action plans includes using non-emitting electricity generation combined with energy consumption reduction measures. If the electricity consumption stays constant even as some portions of the economy are electrified, this is equivalent to an average growth rate of 4.2 TWh starting in 2017. This study shows that if the goal was to decarbonize Canada's economy, the installation rate of clean energy should be over 50 times greater

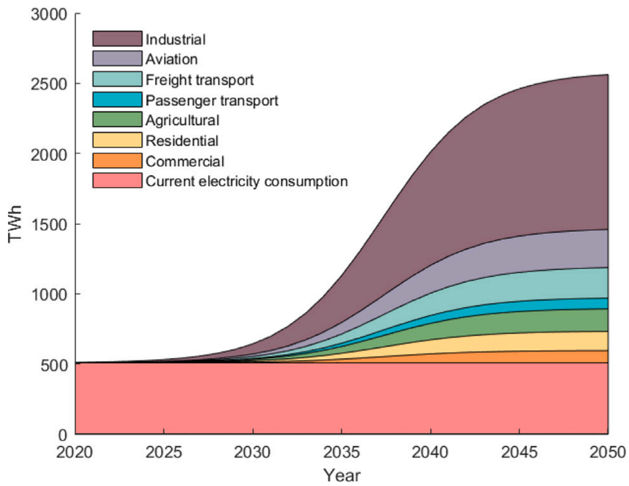


**Fig. 7.** Temporal analysis. The decarbonization of the lower limit of secondary energy would require the installation of 1971 TWh of renewable energy by 2050. The plot is split into the sectors described in Table 1.

and sustained for 2.5 times longer than the objectives set by Canada's current action plan. If the net energy demand increases with economic and population growth, the installation rates would need to be even greater.

## 4. Conclusion

Canada possesses enough land to have solar energy as an alternative to fossil fuels for both its own energy use, as well as for energy exports. This study shows that Canada needs to massively grow its clean energy production if it wants to completely forgo fossil fuels in the future and produce enough e-fuels to replace its fossil fuel exports. Solar projects can provide Canadians with sustainable energy over the long term, providing employment as well as economic and environmental benefits. It would mark a way forward for Canada to maintain and grow its role as an energy producer and help mitigate the GHG emissions responsible for climate change.

The decarbonization of the current electrical grid, secondary energy, and energy exports would require a capacity to generate 7146–8762 TWh of renewable solar energy annually. This is equivalent to 13.4–16.5 times Canada's current carbon-free electricity generation. Based on insolation data from Alberta, this would require 128,500–158,000 $km^2$ of land. This upper limit of land requirement is equivalent to approximately 1.6% of Canada's land mass. Up to 69% of the land needed for this upper limit could come from marginal land which cannot be used for agricultural projects and built-up land. A solar project large enough to decarbonize all energy in Canada could create up to 7.7 million job-years within the energy sector, mitigating job loss from decommissioned oil sand projects as Canada transitions away from fossil fuels.

## CRediT authorship contribution statement

**Carly Bennett:** Conceptualization, Methodology, Resources, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration. **Jocelyn Blanchet:** Methodology, Software, Visualization, Data curation, Formal analysis, Validation. **Keena Trowell:** Conceptualization, Resources, Formal analysis, Validation, Writing – review & editing, Supervision, Project administration. **Jeffrey Bergthorson:** Conceptualization, Resources, Validation, Resources, Writing – review & editing, Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

Funding: This research was supported by the McGill Sustainability Systems Initiative (MSSI) CleanTech for Climate Action Fund, as well as the Natural Sciences and Engineering Research Council of Canada (NSERC).

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