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Article
The Agrivoltaic Potential of Canada

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Abstract: Canada has committed to reducing greenhouse gas (GHG) emissions by increasing the non-emitting share of electricity generation to 90% by 2030. As solar energy costs have plummeted, agrivoltaics (the co-development of solar photovoltaic (PV) systems and agriculture) provide an economic path to these goals. This study quantifies agrivoltaic potential in Canada by province using geographical information system analysis of agricultural areas and numerical simulations. The systems modeled would enable the conventional farming of field crops to continue (and potentially increase yield) by using bifacial PV for single-axis tracking and vertical system configurations. Between a quarter (vertical) and more than one third (single-axis tracking) of Canada's electrical energy needs can be provided solely by agrivoltaics using only 1% of current agricultural lands. These results show that agrivoltaics could be a major contributor to sustainable electricity generation and provide Canada with the ability to render the power generation sector net zero/GHG emission free. It is clear that the potential of agrivoltaic-based solar energy production in Canada far outstrips current electric demand and can, thus, be used to electrify and decarbonize transportation and heating, expand economic opportunities by powering the burgeoning computing sector, and export green electricity to the U.S. to help eliminate their dependence on fossil fuels.

Keywords: agriculture; agrivoltaic; climate policy; Canada; energy policy; farming; land use; photovoltaic; solar energy; renewable energy

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1. Introduction

Due to perpetual decline in solar photovoltaic (PV) systems costs [1,2], the least expensive sustainable source of electricity generation is now solar energy [3]. The cost reductions have become substantial enough that PV-generated electricity can be utilized to subsidize heat pumps, which enables the profitable electrification of natural gas-based [4] or propane-based residential heating in Canada [5]. In addition, the current operational cost of electric vehicles (EVs) warrants electrification of transport [6], which has the potential to be a major economic engine in Canada [7–9]. Lower-cost solar electricity only further incentivizes this transition. Currently, solar based electricity constitutes less than 1% of total electricity generation [10]; however, there is clearly an economic demand for a massive growth in PV to offset fossil fuel electricity generation, heating fuel, and transportation fuel.

Residence in cities has increased worldwide [11], and Canada also has followed this trend with its four largest urban regions (the Calgary—Edmonton corridor, Lower Mainland, Southern Vancouver Island, and all of the Extended Golden Horseshoe in Ontario) currently comprising more than half (51%) of the population [12]. As the cost of PV systems continues to decline, more land is needed for the installation of utility-scale PV systems to power densely populated localities with sustainable electricity. Such PV systems are generally situated in rural agricultural areas [13]. This has the potential to become an issue with rural residents like those observed with wind power siting conflicts [14,15] and, thus, a stepping stone to conflicts over large-scale PV deployment due to apprehensions of possible impedance of agricultural production [16–20]. As the world population continues to increase (1.15%/year) [21], such land use conflicts could intensify as the requirement for food production increases [22]. Historic approaches to convert farmland to a source of energy (i.e., ethanol fuel [23,24]) have proven counterproductive, as they increased food costs as well as global hunger [25]. With a population growth rate of 0.86% per year [26], Canada is already under intense pressure to convert farmland into housing [27,28]. There is a long list of studies that indicate a solution to the energy–land use issue could be through agrivoltaics: the dual use of land for both electricity generation via solar photovoltaic systems and farming [29–33]. An increase in PV system deployment in Canada is beneficial for both local and global environments as solar energy is a sustainable energy source [34]. It shows particular promise in Canada when applied as a dual use on agricultural land [29]. Photovoltaics is a net energy producer, which means the energy consumed during its production is generated multiple times over its warranty lifespan of 25 to 30 years [35], with its technical lifetime being much longer than this [36–38]. The environmental returns become even more favorable as the efficiency of PV systems continues its rise [39] and the energy payback period for PV is now less than a year [40].

Canada is committed to playing its role in the reduction in greenhouse gases (GHGs) and has committed to increase its share of electricity generation through non-emitting sources to 90% by 2030 [41]. Agrivoltaics deployment would solve the issue of land use conflicts on agricultural lands and has the potential to substantially reduce national GHG emissions and help Canada move to renewable energy for electricity, heating, and transport. Previous research has quantified the agrivoltaic potential in the province of Ontario [29] and reviewed agrivoltaic-related policy for the province of Alberta [42]. However, no comprehensive investigation has been undertaken for the sustainable power potential of large-scale agrivoltaics deployment in Canada. To fill this knowledge gap, this paper first reviews the benefits of agrivoltaics and previous agrivoltaic crop studies that could be relevant to Canada. Then, it quantifies the potential of agrivoltaics in Canada. Geographic information systems (GIS) analysis of farming areas in each province of Canada is integrated with PV simulations to achieve this. Sensitivity runs are performed for vertical-mounted and single-axis tracking PV systems. The energy output aggregated for each province and territory through agrivoltaics is compared with the current electricity requirement in Canada. Finally, methods to enable large-scale agrivoltaics are reviewed from policy pathways identified globally.

2. Agrivoltaics Benefits

Agrivoltaics is the dual use of land for both agriculture and PV electricity generation. It is a relatively new technology that overcomes some previous criticisms of large-scale solar PV farms as it ensures agricultural operations continue on farmland. Agrivoltaics provides multiple benefits and services, which are summarized in Figure 1:

- Renewable and sustainable electricity generation;
- Decreased greenhouse gas emissions from offsetting fossil fuel power generation;
- Reduced climate change from reduced carbon emissions;
- Water conservation;
- Increased agricultural crop yields;
- Plant protection on farm from excess solar energy;
- Plant protection on farm from excess wind;
- Plant protection on farm from hail;
- Prevents soil erosion;
- Reverses desertification;
- Maintains agricultural employment;
- Enables production of local food;
- Improved health from the impacts of pollution;
- Increased revenue from the sale of energy for farmers;
- A continued source of income that can acts as a hedge against inflation;

- Energy for servers and cryptocurrency miners;
- Potential for integrated greenhouses;
- Potential to produce on-farm-generated nitrogen fertilizer;
- On-farm production of renewable fuels including hydrogen and anhydrous ammonia;
- Renewable electricity generation to charge EVs for both on- and off-farm use.

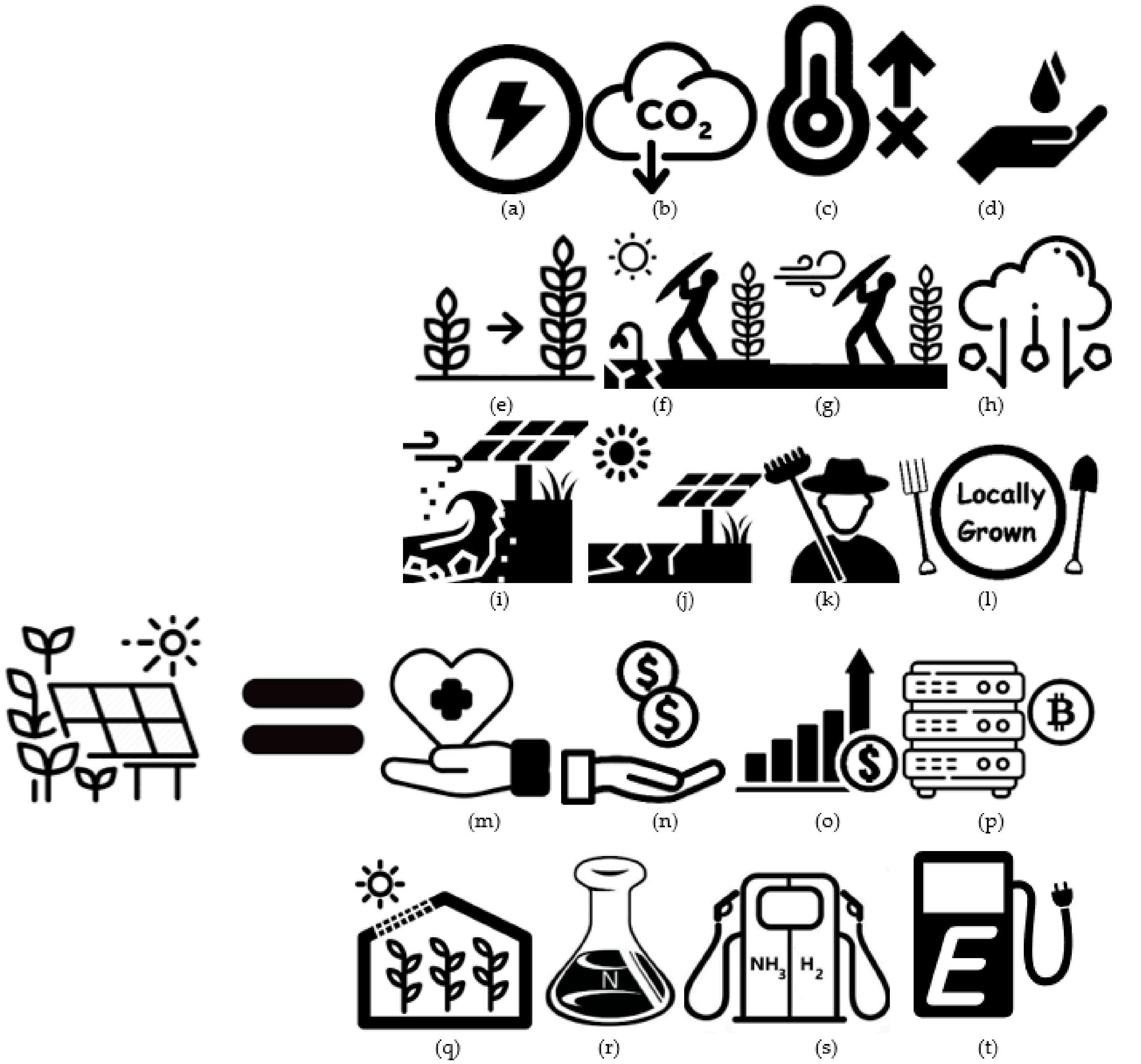

Figure 1. Services and benefits provided by agrivoltaic applications include: (**a**) renewable electricity generation, (**b**) decreased greenhouse gas emissions, (**c**) reduced climate change, (**d**) water conservation, (**e**) increased crop yield, (**f**) plant protection on farm from excess solar energy, (**g**) plant protection on farm from excess wind, (**h**) plant protection from hail, (**i**) prevents soil erosion, (**j**) reverses desertification, (**k**) maintains agricultural jobs, (**l**) local food production, (**m**) improved health by reducing pollution for power generation, (**n**) increased revenue for farmers, (**o**) an economic hedge against inflation, (**p**) energy for servers and cryptocurrency miners, (**q**) integrated greenhouses, (**r**) on-farm production of nitrogen fertilizer, (**s**) production of renewable fuels on farm such as hydrogen or anhydrous ammonia, and (**t**) electricity generation for EV charging.

The first two agrivoltaic benefits come directly from the fact that solar photovoltaic systems generate renewable and sustainable electricity and that when this green electricity offsets electricity from fossil-fuel-generated sources, GHG emissions are reduced [43]. This, in turn, reduces global climate destabilization and the long list of adverse effects on the economy, human health, and the environment [44]. Agrivoltaics also has the potential to benefit water systems by improving farm water efficiency and water conservation [45–48]. Agrivoltaic arrays can be used to power both drip irrigation [49], which is far more efficient than spraying, and vertical farming [50], which uses a small fraction of the water resources demanded by field-based crops.

Most importantly, many studies on a wide variety of food crops have now demonstrated that agrivoltaics ***increases*** crop yield, which include:

- Basil [51];
- Broccoli [52];
- Celery [53];
- Chiltepin peppers [54];
- Corn [55]/maize [56–59];
- Lettuce [32,60];
- Pasture grass [61];
- Potatoes [62];
- Salad [62];
- Spinach [51,62];
- Tomatoes [54];
- Wheat [56–58].

Due to the modest or even substantial positive impacts on yield of the wide variety of produce summarized above, the land use efficiency increases for agrivoltaics over side-by-side farming and PV [63], and, thus, the land productivity could increase by 35–73% globally [64]. Agrivoltaic arrays generate microclimates beneath the solar PV arrays that alter several factors including the relative humidity, air temperature, both wind speed and direction, and moisture of the soil [61]. This microclimate is often beneficial to food crops because the solar PV array acts as a shield to protect crops from excess solar energy. Agrivoltaic systems also acts as wind shields and protect plants/cultivars from heavy wind loads [65]. This same PV shield concept can protect crops from hail, while simultaneously increasing PV performance due to lower operating temperatures created by the crops beneath the modules [30,54,66]. Agrivoltaic microclimates also can mitigate soil erosion [67] and can even be used to rehabilitate deserts [68] and barren land [67] to grow plants there.

Agrivoltaics, when designed appropriately, can minimize agricultural displacement for energy [33,64,69]. It maintains local agricultural employment and continues to enable local food production, which provides the environmental and health benefits of reducing the distance food travels [70–73]. Along with the known health benefits from fresh food, agrivoltaics decreases the many health problems associated with fossil fuel combustion by displacing these fuels [73]. Thus, agrivoltaics can both directly and indirectly improve human health and prevent premature deaths [74]. Agrivoltaics also helps to mitigate Scope 1, 2, and 3 emissions [75]. Scope 1 emissions reduction is due to the reduced travel/commute of products that traditionally need to be remotely produced and brought onto farms for cultivation such as fuel, electricity, and fertilizers—agrivoltaics enables the on-farm production of these products. Scope 2 emissions reduction is achieved as farming operations can use electric vehicles which can be charged from electricity generated on-farm via agrivoltaic technology. The same electricity can be used for other farming operations. Scope 3 emissions reduction is possible if electric vehicles are used to transport the produce from the farm, which can, again, be charged using on-farm-generated electricity, thus alleviating the emissions generated by vehicles during travel. Scope 3 GHGs are indirect emissions that are released in the supply chain of goods and services. Agrivoltaics also increases the crop revenue for a given acre [76], which can help farmers economically. In addition, as the solar PV system is a capital asset that generates economic value that increases with inflation, it can be viewed as a financial means to hedge against inflation during times of high inflation [77]. Agrivoltaics can be coupled to large loads from computing facilities such as those running AI, server farms, and cryptocurrency miners [78]. There is a particularly good potential symbiosis between server waste heat, greenhouses, and agrivoltaics for powering both systems [79]. Partially transparent PV can be integrated into greenhouse glazing itself, providing further coupling between solar electricity generation and food production [80–82].

Agrivoltaic-generated electricity can also be used to provide direct farm inputs such as on-farm production of fertilizers (e.g., nitrogen fertilizer) [83] and renewable fuels (e.g., (anhydrous ammonia [84] and hydrogen fuel [85–87]). Agrivoltaics can be used for EV charging for on-farm use or to sell as a commodity, particularly if a farm is located next to a major road that is appropriate for an EV charging park, which, in turn, would help to accelerate the electrification of transport by reducing range anxiety.

Agrivoltaic systems are appropriate over a vast array of different scales. Generally, agrivoltaics are considered for large-scale (utility-scale) applications; however, even for a home planter, parametric open source cold-frame agrivoltaic systems are feasible [88]. The technology can operate with a variety of shade tolerance in crops. For instance, full array density PV modules work well with shade-tolerant crops, while less dense PV systems are favorable for shade-intolerant crops [89]. This is because the crops that are more sensitive to shading require more sunlight for growth. As the racking density is increased (full array density PV modules), less sunlight reaches the plants and this impacts their growth. However, cultivars that are tolerant to shading grow well even with high racking density systems. East/west-facing vertical bifacial photovoltaics can be a preferred scheme for agrivoltaics with field crops using conventional farm equipment [89]. By increasing the installation height of PV arrays, more irradiance and bifacial gain is observed for bifacial modules [90]. Another advantage of elevating the height of PV panels is the ease of operation of agricultural machinery. Increasing inter-row spacing between modules benefits ground irradiation; however, it also reduces electrical output for a given area [90]. With agrivoltaics row spacing greater than conventional PV farms, the capacity factor would be increased due to freer air flow resulting in lower operating temperatures as well as radically reduced row-to-row shading. A small increase in the DC losses would be expected because of longer cable lengths, but, overall, the agrivoltaics system would provide economic advantages, enabling more land to be used in total. South-facing nearly conventional systems are beneficial for farming shade-tolerant crops, whereas some types of east–west vertical arrays are advantageous for permanent crops (e.g., species that are harvested over many seasons such as grapes) [90].

Agrivoltaics technology is already used in Canada, with projects such as the Arnprio tri-part agrivoltaics project, which combines bee and honey production, monarch butterfly conservation, and solar grazing for vegetation control [91]. At present, most agrivoltaics systems employed in Canada consist of traditional solar PV farms, which are also used for grazing sheep. Such systems are beneficial for the sheep as they provide thermal protection [92] and improved quality grazing areas [93], as well as for the PV systems as the sheep alleviate the cost of weed removal. Life cycle analysis of such agrivoltaic sheep operations show that they are environmentally beneficial [94] but fail to reach the full potential of agrivoltaics that are designed around crop production.

Unfortunately, Canada is behind Asia, Europe, and the U.S. in agrivoltaic deployments. Nations that are more aggressive at deploying agrivoltaics are expected to gain a competitive advantage due to the benefits outlined in Figure 1. Being the fifth largest agricultural exporter globally [95], Canada's motivation to keep up with novel agricultural technologies is high. As PV-generated electricity is already a low-cost option (i.e., Alberta PV is currently at CAD 47/MWh for a power purchase agreement (PPA) [96]) and agrivoltaics has all the benefits summarized in Figure 1, future utility-scale PV installations in Canada could favor agrivoltaics. The remainder of this article will determine the potential for agrivoltaics in Canada if such a policy were to be pursued.

3. Materials and Methods

This study was carried out to determine the agrivoltaics potential in Canada using 1% of the existing available farmland in Canada. First, the total solar potential across Canada was determined using a vector dataset that estimates the photovoltaic potential (in kWh/kWp, where 'kWp' is the peak power of PV panel) of south-facing, vertically oriented arrays across the country [97]. This gives the energy output (kWh) for a solar PV system of 1 kW peak power installed within those regions annually. From this layer, the area representing the cropland in each province (Ontario, Alberta, Saskatchewan, Manitoba, British Columbia, Quebec, and the Maritimes combined) was extracted based on the 2015 Land Cover of Canada 30 m spatial resolution raster dataset [98]. ArcGIS Pro 2.9.0 with the Spatial Analyst toolbox was used to achieve this. It should be pointed out that "pastureland" was excluded from the dataset although it could increase the agrivoltaic potential of Canada further. This consideration is left for future work. The total conventional PV potential area, A_p, for each province was then determined from the area of the cropland raster cells and average PV potential of each using:

$$A_p = N \times A_r \times B_{PV}\ [m^2] \quad (1)$$

where N is the number of raster cells per band per province, A_r is 900 m^2/raster cell, and B_{PV} is the average PV potential per band.

The GIS procedure started by extracting cropland raster cells from the 2015 Land Cover of Canada using the "Extract by Attributes" tool. Each cell was 30 × 30 m in size, resulting in a total area of 900 m^2. The vector polygons of annual photovoltaic potential (kWh/kWp) in a south-facing, vertically oriented array from Natural Resources Canada were then converted to a raster using the "Polygon to Raster" tool with the same cell size as the Land Cover data. The value was reclassified to represent the average kWh/kWp of each solar band using the tool "Reclassify". New polygon feature layers were created for the outlines of provinces and the "Clip Raster" tool was used to clip the raster to these provinces. The "Build Pyramids" tool was run on all raster layers to improve the ease of display. The count and value for each layer could then be viewed by right clicking on the layer and selecting "Attribute Table" and the above formula applied.

Locations in each major solar flux grouping were used to model agrivoltaic systems in the opensource System Advisor Model 2022 (SAM) [99] using Heliene 144HC-460 bifacial PV modules [100]. SAM is a technoeconomic, free, open-source tool that performs modelling of several renewable energy systems including photovoltaics. The program is easy to use and includes directories of PV panels, inverters, and other components available in the market, thus providing a close-to-realistic solution. Moreover, it incorporates MPPT controllers, which optimize the energy production of solar panels. Different types of systems could be chosen based on the application of work such as residential or commercial, single owner or third-party owner, etc. The software also allows parametric analyses for optimizing any renewable energy project.

For this study, one percent of agricultural land was calculated for each province in Canada as the area of interest. To determine the configuration of PV systems in this piece of land, the area was considered as a square and the length of one side was calculated by taking the square root. Two distinct agrivoltaics systems are considered for the analysis: (1) vertical (south-facing, tilt 90°) (Figure 2a) and (2) single-axis tracking (horizontal, tilt 0°, which is the default setting in SAM for single-axis tracking modelling) (Figure 2b). The vertical PV system allows easy access to agricultural land as well as convenience of operation of agricultural machinery. Moreover, the farmers do not need to be concerned about the height of their produce/plants and the PV arrays, which makes this type of system quite favorable for agrivoltaics applications on open fields. On the other hand, single-axis tracking systems are employed to extract the maximum solar energy on the electrical side per unit area. Tracking may also provide an option to orient the panels vertically so that the farmers can work conveniently on their farmland. The design of a single array of vertical PV takes up a width of 4.8 m with an installed PV capacity of 2700 W [101]. The design of a single array of single-axis tracking system takes up a width of 23 m and depth of 4 m with an installed PV panel capacity of 15,000 W [102].

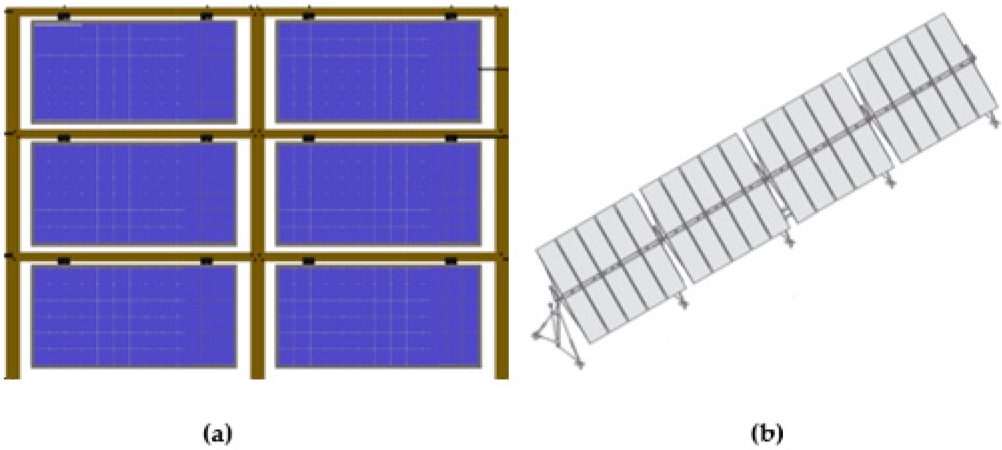

Figure 2. (**a**) Vertical PV system array (adapted from [101]) and (**b**) single-axis tracking system array (adapted from [102]).

The length of one side of square land area is divided by the width of the array (4.8 m for a vertical system and 23 m for a single-axis tracking system) to determine the total number of arrays in one row. To calculate the number of rows on the piece of land, the length of one side is divided by 20 m for both systems to ensure sufficient distance for farm equipment mobility—the inter-row spacing considered for agrivoltaics system. Once the number of rows is ascertained, then, using the number of vertical and single-axis tracking arrays in a single row, the total number of arrays in an area is determined. Next, the product of the total number of arrays and installed PV capacity on a single array (2700 W for vertical system and 15,000 W for single-axis tracking system) provides the total installed PV capacity on the agricultural land. The following locations were chosen for each province based on the energy yield potentials from GIS analysis:

- Alberta (Edmonton, Drumheller);
- British Columbia (Richmond, Dawson Creek);
- Manitoba (Winnipeg, Brandon);
- Maritimes (Cardigan, New Glasgow);
- Ontario (London, Chatham, Gameland);
- Quebec (Sherbrooke);
- Saskatchewan (Northern Pine, Regina).

Next, the cities inside each province that match these potentials were identified and selected for SAM analysis. British Columbia was an exception. Richmond was selected for energy yields of 650 kWh/kWp, 750 kWh/kWp, and 850 kWh/kWp as there was no identified location close to the areas of energy yield potentials of 650 kWh/kWp and 850 kWh/kWp to use in British Colombia. Richmond has an average energy yield potential of 750 kWh/kWp, which is the average for the region.

Using these locations, SAM models (Table 1) were developed to determine the annual energy yield for one kW of PV system for both the configurations. Finally, using the total installed capacity for an area and annual energy yield of the system, the total agrivoltaics potential of the location was determined.

Table 1. SAM input parameters for detailed PV model.

Parameters	Vertical	Single-Axis
PV Module	Heliene 72M-405 G1 Bifacial	
Module Type	Mono Crystalline Silicon—Bifacial	
Bifaciality	0.7	
Tracking and Orientation	Fixed	1 Axis
Tilt Angle	90 (tilt—latitude in SAM)	0 * (tilt—latitude in SAM)
Azimuth	180 degrees	
DC Power Rating	1.2 kWdc	
DC to AC Ratio	1.0	
Soiling Losses	5%	
DC Power Losses	4.44%	
AC Power Losses	1%	
PV Degradation Rate	0.5%	
Lifetime	25 years	

* Default setting in SAM for 1-axis tracking system are based on [103].

4. Results

Using GIS analysis, the available potential for a conventional solar PV was determined, as shown in Figure 3.

The energy yield at sample locations within each province was then calculated, which provided similar results (kWh/kWp) to those from the GIS analysis. These results are shown in Table 2.

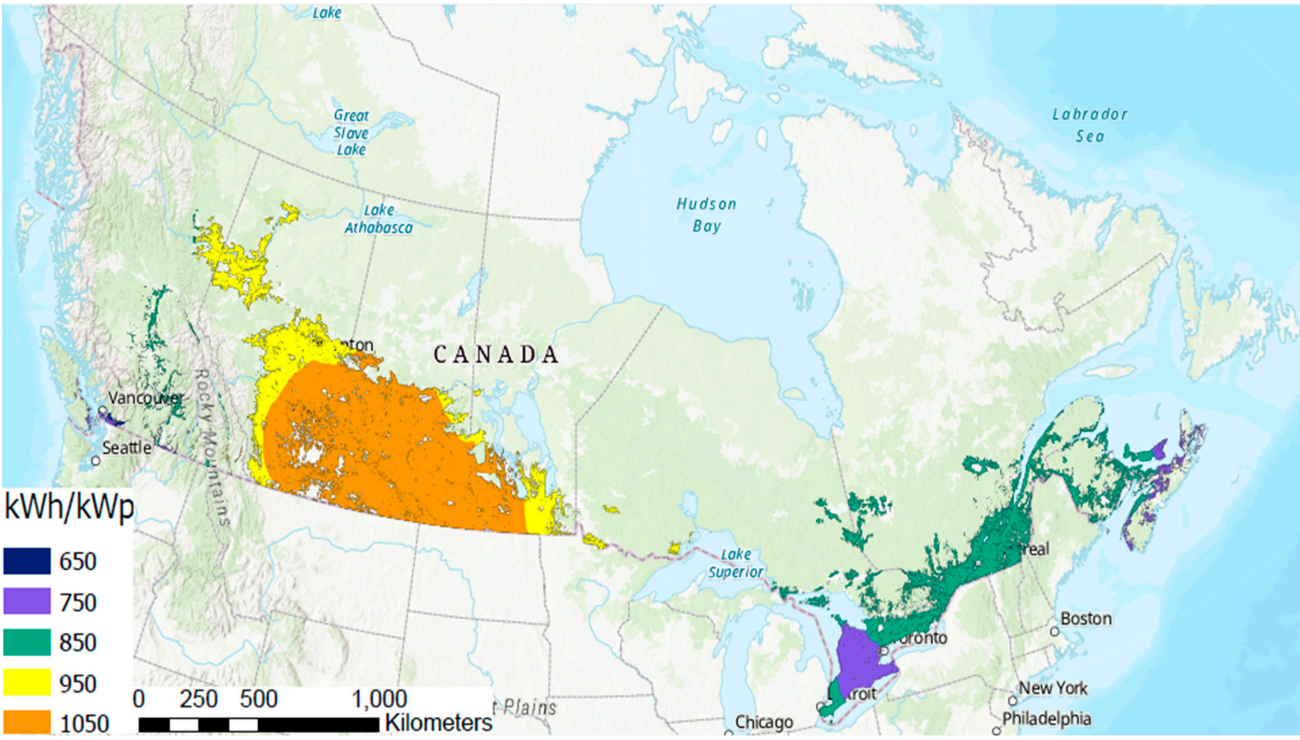

Figure 3. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across Canada [97,98,104].

Table 2. Locations in individual provinces.

Conventional PV Potential (kWh/kWp)	Ontario	Alberta	Saskatchewan	Manitoba	British Columbia	Quebec	Maritimes
	Locations						
650	-	-	-	-	Richmond	-	-
750	London	-	-	-	Richmond	-	Cardigan
850	Chatham	-	-	-	Richmond	Sherbrooke	New Glasgow
950	Gameland	Edmonton	Northern Pine	Winnipeg	Dawson Creek	-	-
1050	-	Drumheller	Regina	Brandon	-	-	-

The results of the analyses are described below for individual provinces.

4.1. Ontario

Although Ontario is a large province, the vast majority of the farmland is located in the south, as shown in Figure 4. There are three solar flux regions quantified in Table 3, with the largest being the 750 kWh/kWp region. The highest flux zones are located in the western part of the province and are a factor of 20 smaller in area than the other two flux farmland zones. The potential solar energy yield on only 1% of this land is still substantial, with vertical arrays offering over 17,000 GWh/year and more than 30,000 GWh/year if a single-axis tracker is used. In 2019, Ontario generated 153.0 terawatt hours (TWh) of electricity and only 8% was carbon emitting [105]. Thus, to eliminate all carbon emissions from the Ontario grid, only 12 TWh would need to be produced. Therefore, less than $\frac{1}{2}$ a percent of farmland would need to be converted to single-axis trackers to make the Ontario electric grid net zero emissions. This trivial amount of farmland moving to agrivoltaics is likely to increase production, but there are policy hurdles that need to be overcome [29] to enable farmers to enjoy the benefits detailed in Figure 1.

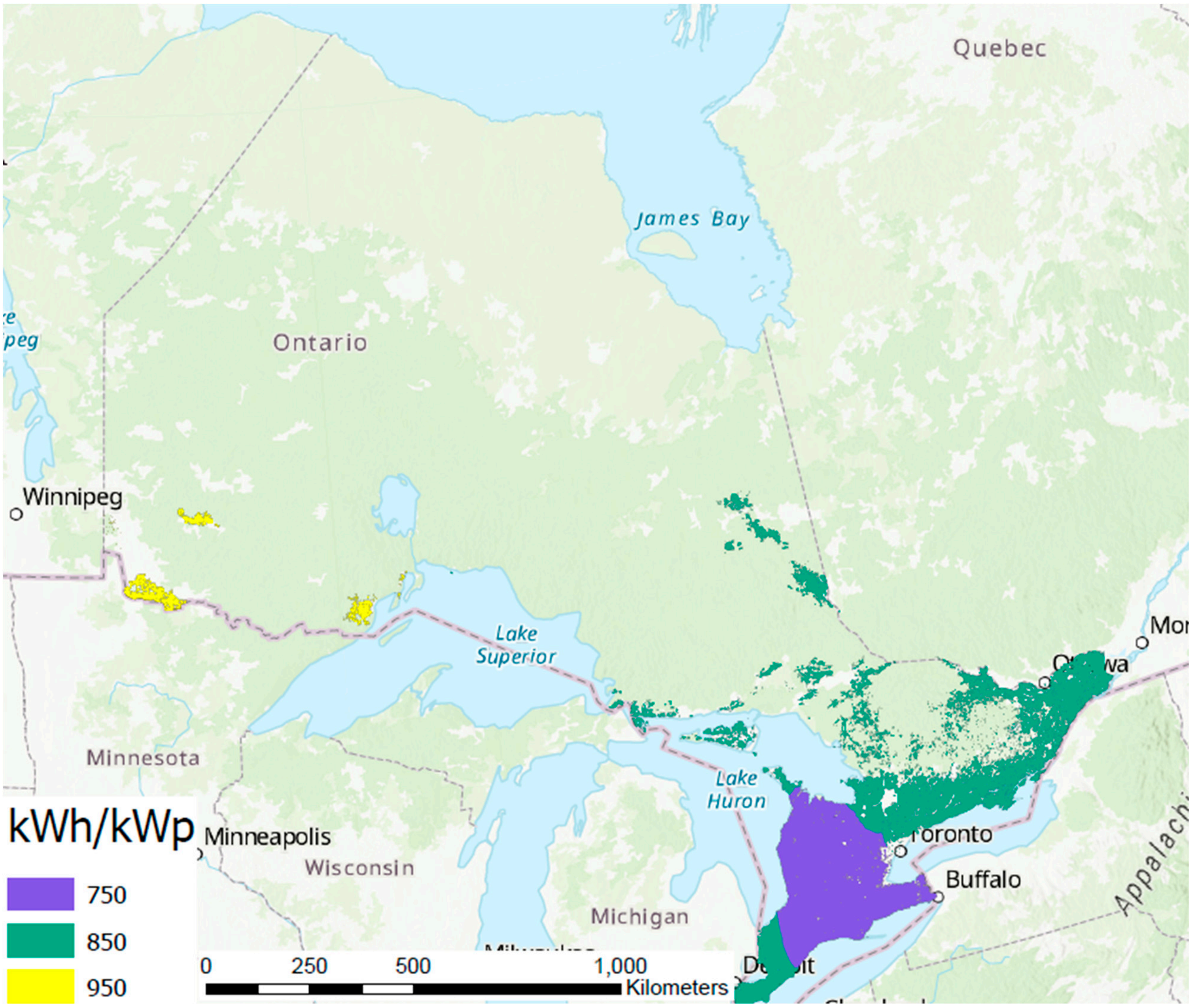

Figure 4. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across Ontario [97,98,104].

Table 3. Potential of agrivoltaics in Ontario for 1% of agricultural land.

Conventional PV Potential (kWh/kWp)	Ontario	
	Vertical (GWh/year)	Single-Axis Tracking (GWh/year)
750	8566	15,178
850	8075	14,460
950	487	751
Total	**17,128**	**30,389**

4.2. Alberta

The province of Alberta shares its borders with Saskatchewan and British Columbia. Most of the agricultural land in Alberta is in the south, adjacent to Saskatchewan, as depicted in Figure 5. The PV potential on this agricultural land falls under two high-solar flux bands, 950 kWh/kWp and 1050 kWh/kWp, making it one of the locations most conducive to PV deployment. As can be seen in Table 4, through agrivoltaic installation on only 1% of its agricultural land, the electricity output from vertical PV systems would be greater than 48,000 GWh/year. The energy output could be greatly enhanced if single-axis tracking technology is employed, making it more than 73,000 GWh/year. This is nearly the entire electricity production of Alberta, which generated approximately 76 TWh of electricity in 2019 [106]. 89% of Alberta's electricity came from fossil fuels, yet single-axis tracking agrivoltaics on 1% of the current agricultural land would eliminate the GHG emissions from combusting these fuels entirely. From a GHG emissions mitigation standpoint, agrivoltaics has an enormous potential in Alberta for helping eliminate Canada's overall emissions.

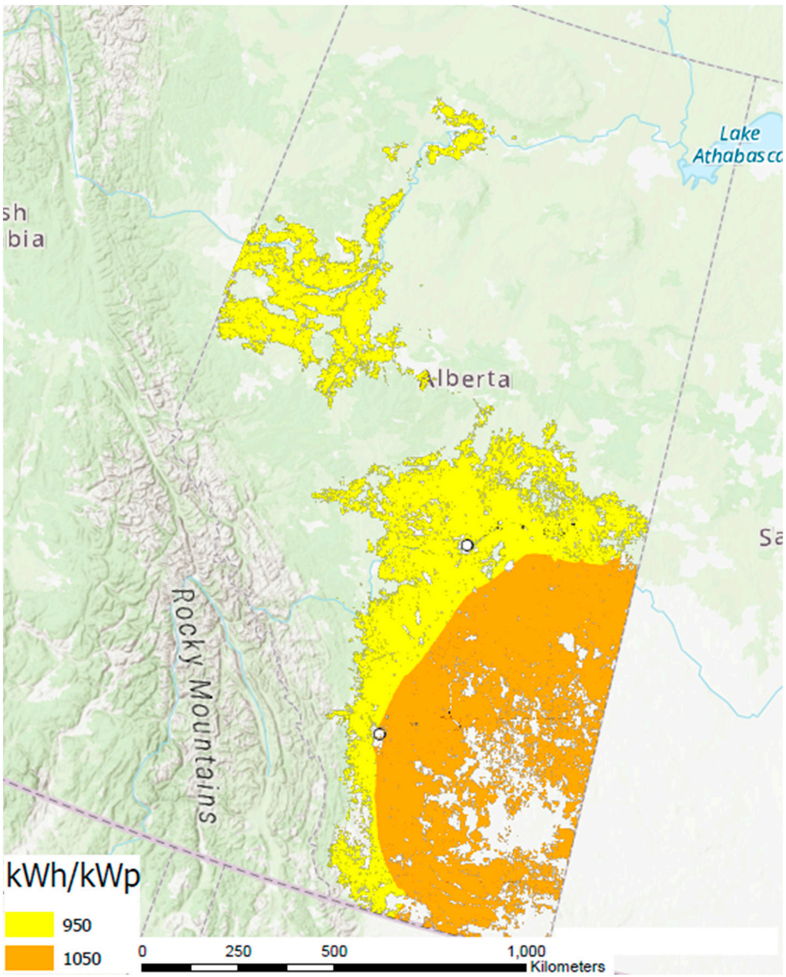

Figure 5. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across Alberta [97,98,104].

Table 4. Potential of agrivoltaics in Alberta for 1% of agricultural land.

Conventional PV Potential (kWh/kWp)	Alberta	
	Vertical (GWh/year)	Single-Axis Tracking (GWh/year)
950	23,567	34,899
1050	24,669	38,165
Total	**48,236**	**73,064**

4.3. Saskatchewan

Saskatchewan, the province with the largest agricultural land, accounted for almost 2/5th of crop field farmland in Canada in 2016 [107]. Its agricultural land is concentrated in the south, as seen in Figure 6. Saskatchewan receives high solar flux across its cropland, with a solar yield potential of approximately 1050 kWh/kWp. Using only 1% of this area for agrivoltaics would provide 76,087 GWh/year of electricity from vertical PV racking designs and more than 116,000 GWh/year from single-axis tracking installations (Table 5). In 2019, Saskatchewan produced 24.1 TWh of electricity, with its majority (81%) coming from fossil fuels [108]. The analysis shows that by using only a tiny fraction (about 0.17–0.26%) of agricultural land for agrivoltaics, the province can completely offset fossil fuel-based electricity generation and contribute positively towards Canadian renewable energy goals.

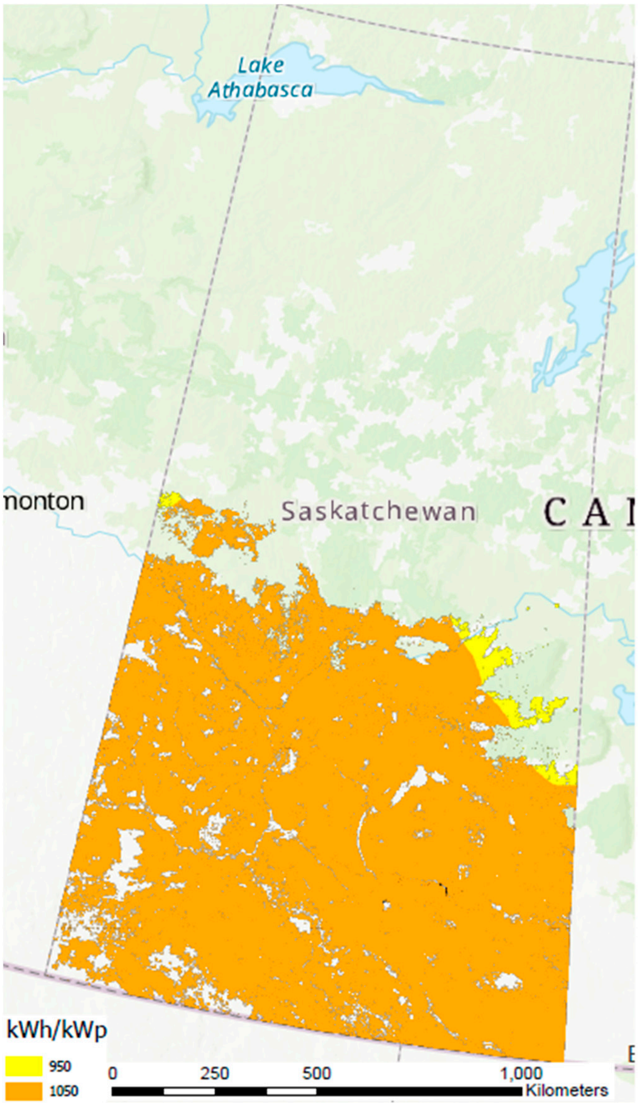

Figure 6. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across Saskatchewan [97,98,104].

Table 5. Potential of agrivoltaics in Saskatchewan for 1% of agricultural land.

Conventional PV Potential (kWh/kWp)	Saskatchewan	
	Vertical (GWh/year)	Single-Axis Tracking (GWh/year)
950	1123	1664
1050	74,964	115,011
Total	**76,087**	**116,675**

4.4. Manitoba

Farmland with the highest solar flux lies to the south of the region, adjacent to Saskatchewan (Figure 7). The solar energy yield for Manitoba's agricultural land falls under two solar flux regions, 950 kWh/kWp and 1050 kWh/kWp, which are somewhat evenly shared across the province. Numerical simulations indicate that by using only 1% of this farmland, Manitoba can annually generate approximately 19,000 GWh/year of electrical energy by adopting vertical racking designs and 29,835 GWh/year using single-axis tracking systems (Table 6). Data from 2019 show that total electrical energy generated in the province was around 34 TWh [109]. Manitoba electricity generation is already 98% renewable with hydroelectric and wind. Thus, using 1% of farmland for agrivoltaics (single-axis tracking PVs) has the potential to meet almost all the electrical energy requirements of the province or to provide renewable electricity for export.

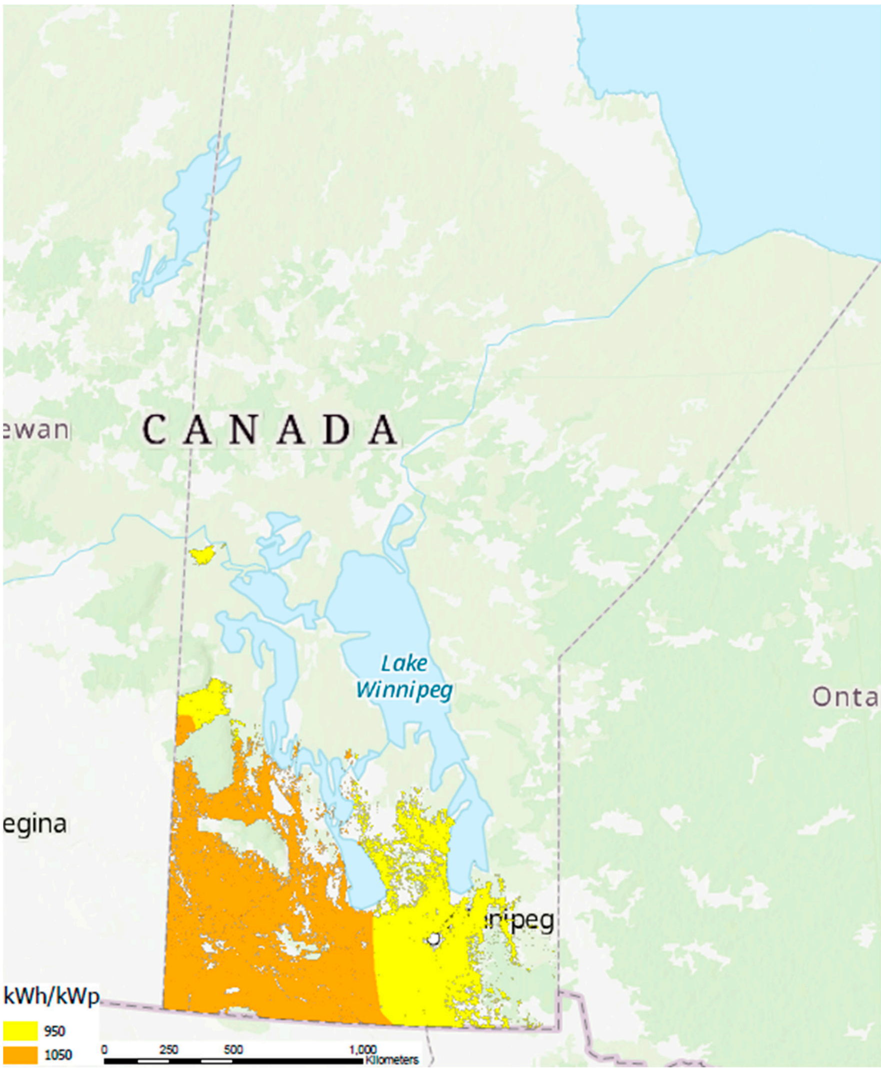

Figure 7. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across Manitoba [97,98,104].

Table 6. Potential of agrivoltaics in Manitoba for 1% of agricultural land.

Conventional PV Potential (kWh/kWp)	Manitoba	
	Vertical (GWh/year)	Single-Axis Tracking (GWh/year)
950	6905	10,566
1050	12,132	18,819
Total	**19,037**	**29,385**

4.5. British Columbia

British Columbia lies in the southwest of Canada. The total farmland in British Columbia is small and is concentrated in two regions near Vancouver and Dawson Creek, with the rest distributed across various valleys (Figure 8). Each of these receives a different solar flux from 650 kWh/kWp to 950 kWh/kWp. These values are some of the poorest solar resources in Canada. Despite this, using 1% of the agricultural land for agrivoltaics for vertical PV arrays and single-axis tracking system arrays would supply 2551 GWh/year and 4007 GWh/year, respectively (Table 7). The total energy generation in the provinces was approximately 64 TWh in 2019 [110], but 87% of its electricity is from hydroelectricity and, thus, is already renewable in nature [110]. Almost 5% of the electricity generated in British Columbia in 2019 came from natural gas (4%) and petroleum (0.5%). Less than 1% of agricultural land requires single-axis tracking agrivoltaics installation to eliminate fossil fuel-based electricity in the province.

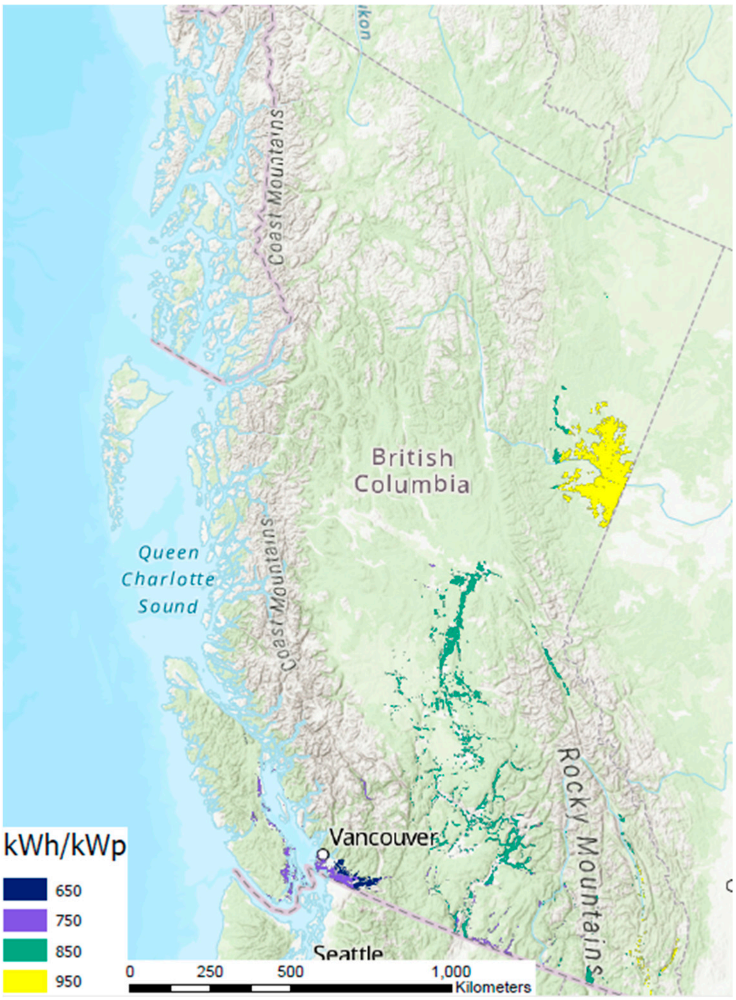

Figure 8. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across British Columbia [97,98,104].

Table 7. Potential of agrivoltaics in British Columbia for 1% of agricultural land.

Conventional PV Potential (kWh/kWp)	British Columbia	
	Vertical (GWh/year)	Single-Axis Tracking (GWh/year)
750	957	1671
950	1594	2336
Total	**2551**	**4007**

4.6. Quebec

The province of Quebec is the largest province of Canada in terms of land area [111]. As seen in Figure 9, most of its agricultural land is situated in the south, with solar PV potential around 850 kWh/kWp. The conversion of 1% of the province's agricultural land to agrivoltaics using vertical PVs would provide an annual electricity generation potential of 9456 GWh/year for the region. The potential is increased to 14,560 GWh/year if single-axis trackers are used (Table 8). Most of the electricity in Quebec is from hydropower. In 2019, Quebec generated 212.9 TWh of electricity and only 0.3% came from fossil fuels (natural gas and petroleum) [112]. Only a tiny fraction (less than 0.1% regardless of the type of agrivoltaics) of agricultural land would need agrivoltaics installations in Quebec to completely eliminate emissions from fossil fuel used for electricity generation.

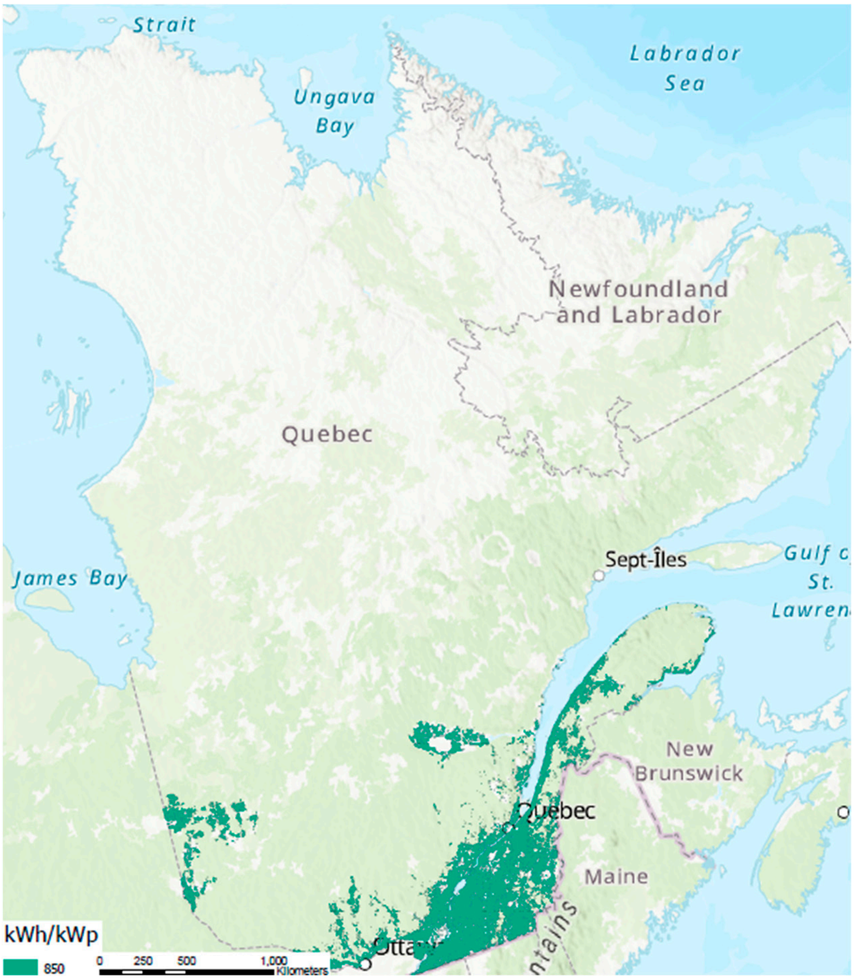

Figure 9. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across Quebec [97,98,104].

Table 8. Potential of agrivoltaics in Quebec for 1% of agricultural land.

Conventional PV Potential (kWh/kWp)	British Columbia	
	Vertical (GWh/year)	Single-Axis Tracking (GWh/year)
850	9456	14,560
Total	**9456**	**14,560**

4.7. Maritimes

New Brunswick, Nova Scotia, and Prince Edward Island form the Maritime provinces of Canada [113]. The two bands of the solar flux with a PV potential of 750 kWh/kWp and 850 kWh/kWP are scattered across the region's agricultural lands, as shown in Figure 10. From SAM analysis, 2772 GWh/year of electricity generation is offered by the province if vertical PV systems are used for agrivoltaics. The power generation potential augments to 4474 GWh/year if a single-axis tracking system is used as shown in Table 9. The Maritimes are heavily fossil fuel-dependent and have relatively small agricultural areas, so to eliminate all carbon emissions from the electric grid for the Maritimes, 4.1% of agricultural land is needed for vertical PV and 2.5% for single-axis tracker agrivoltaics.

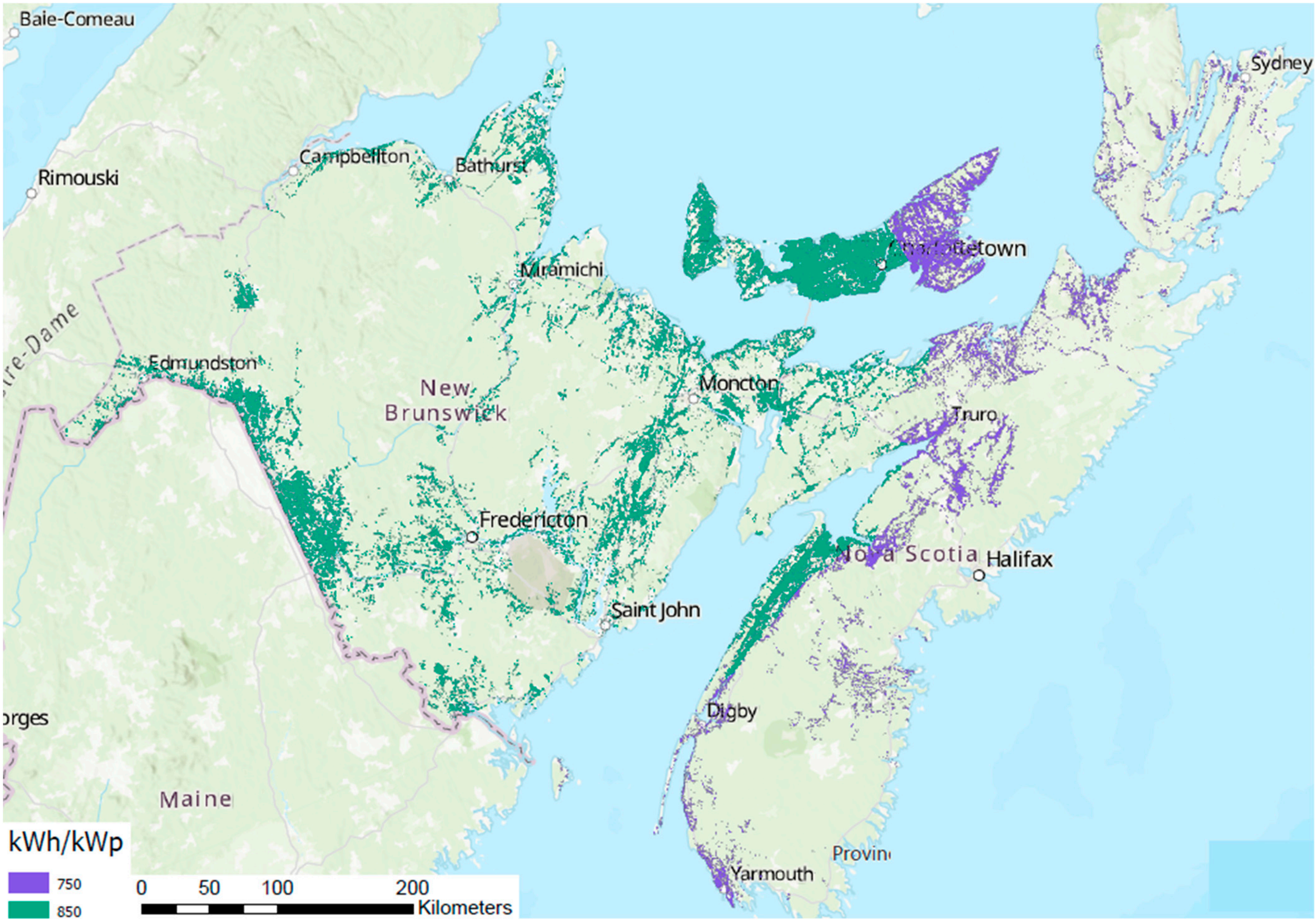

Figure 10. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across the Maritimes [97,98,104].

Table 9. Potential of agrivoltaics in the Maritimes for 1% of agricultural land.

Conventional PV Potential (kWh/kWp)	Maritimes	
	Vertical (GWh/year)	Single-Axis Tracking (GWh/year)
750	714	1156
850	2058	3318
Total	**2772**	**4474**

5. Discussion

From SAM models and simulations, it is estimated that the potential annual energy output by employing agrivoltaics on 1% of agricultural land is 175,267 GWh for vertical systems or 272,554 GWh for single-axis tracking systems in Canada. Table 10 summarizes the electricity generation potential of agrivoltaics installation on 1% of agricultural land within the provinces of Canada.

Table 10. Electricity potential of agrivoltaics installation on 1% of Canadian agricultural land.

Province	Vertical (GWh/year)	Single-Axis (GWh/year)
Ontario	17,128	30,389
Alberta	48,236	73,064
Saskatchewan	76,087	116,675
Manitoba	19,037	29,385
British Columbia	2551	4007
Quebec	9456	14,560
Maritimes	2772	4474

Canada's total electrical energy production in 2019 was 632,200 GWh [114]. Thus, about 28% or 43% of Canada's electricity needs can be catered for from vertical bifacial or single-axis trackers agrivoltaics systems, respectively. Considering Canada's targets for renewable energy generation and reduced GHGs, agrivoltaics technology manifests immense potential. Table 11 summarizes the percentage of agricultural land on which agrivoltaics needs to be deployed to eliminate fossil fuel-based electricity generation in Canada.

Table 11. Percentage of agricultural land by province required to eliminate emissions from fossil fuel-based electricity generation in Canada.

Province	Vertical (%)	Single-Axis (%)
Ontario	0.71	0.40
Alberta	1.40	0.92
Saskatchewan	0.26	0.17
Manitoba	0.0036	0.0023
British Columbia	1.12	0.72
Quebec	0.067	0.044
Maritimes	4.5	2.5

This study provides an in-depth evaluation of agrivoltaics potential in each province of Canada. The results could be used to formalize future policies and regulations, which will then help unlock the technology's full potential.

5.1. Limitations

Although this investigation demonstrates capabilities of agrivoltaics technology in Canada, there are limitations to this study. Firstly, there is a need to experiment with on-ground agrivoltaics systems that provide experimental evidence for both the electrical output and the performance of crops under the system. Thus, future work is required to translate simulations and model-based study into practical applications. Additionally, this study did not include the Canadian territories (The Northwest Territories, the Yukon, and Nunavut), which could be investigated in the future. Moreover, there are several agrivoltaics configurations that need to be studied (for instance, vertical bifacial, single- and double-axis tracking, fixed and variable tilt, stilt-mounted systems or conventional systems, etc.) with a variety of crops. Studies are also needed to understand the technical challenges that may arise when such a large number of solar farms are connected to the electric grid (e.g., transmission and distribution system upgrades). Further, additional experimental studies are needed to determine the impact of farming debris on PV system production in the two configurations considered here. The cleaning requirements of solar PV systems needed to optimize output, especially for dust and snow, is an area which requires further investigation.

Currently, little research focuses on the quality of crops that will be harvested under agrivoltaics. Hence, detailed investigation is required to determine if agricultural produce via agrivoltaics improves or deteriorates the nutrient profile. Moreover, social acceptance of the technology is key to its diffusion on commercial scale. Hence, studies are required which focus on people's perceptions (and misconceptions) about the technology and seek feedback from the main stakeholders, which will promote its adoption on mass-scale. Moreover, a detailed economic analysis is required to ascertain the total capital investment needed for agrivoltaics projects in each area and the expected rate of return for optimized systems (including increased crop values as well as electricity production). Such studies will serve as the foundation of financial models, which help farmers, financers, and policy makers to make informed decisions.

5.2. International Competition in Agrivoltaics

The agrivoltaics projects employed in Canada thus far are relatively small in scale and consist primarily of traditional solar PV systems, which are used for livestock grazing. These projects have been shown to be helpful for both sheep grazing (benefits include protection from heat [92] as well as provision of high-quality grazing land [93]) and PV systems (advantages include alleviated maintenance costs associated with weed removal, etc.), and when combined, for the overall ecosystem/environment as well [94]. The merits of agrivoltaics technology go far beyond these, as can be seen in Figure 1, and the technology can offer better land use strategies. Canada needs more aggressive development and advancement in agrivoltaics to keep up with the rest of the world, especially Europe, China, Japan, and U.S., where the technology is rapidly expanding. In 2012, there was only 5 MW of agrivoltaics systems installed globally; this has expanded to a total global installed capacity reaching 14 GW in 2021 [115]. In China, the largest agrivoltaic system has an installed capacity of 700 MW, whereas Japan has 1800 small agrivoltaic systems [115]. This shows the scale at which agrivoltaic technology has progressed and the flexibility it has with deployment. Moreover, approximately 2800 MW of agrivoltaics systems have been installed in U.S. [116]. The U.S. Department of Energy recently approved USD 8 million to support agrivoltaics research and supplement its development [117]. Canada, being one of the largest exporters of agricultural products [95], has substantial revenue at stake and needs to consider what appropriate actions are needed to stay competitive with other countries that are both deploying and researching agrivoltaics aggressively.

5.3. Potential Use of Agrivoltaic-Generated Electricity: Computation, Transportation, and Export

As the results in Table 11 clearly show, augmenting even tiny fractions of the agricultural land in Canada with agrivoltaics would eliminate all carbon emissions from Canada's electricity generation. This is important as Canada's per capita historic GHG emissions are the highest in the world [118] and the existence of the new agreement on "loss and damage fund" [119,120] can make further emissions a major liability. Canada should be aggressively seeking to reduce carbon emissions liabilities [121–124]. It is also clear that the agrivoltaic potential of all the provinces far exceeds what is needed to decarbonize the electric system (Table 11). There are several applications of low-cost sustainable electricity generation that would benefit from a large influx of agrivoltaics deployments in Canada:

(i) decarbonizing transportation by moving to electric vehicles [125,126] and hydrogen fuel (e.g., mirror the hub and spoke collection system developed by dairy producers for on-farm hydrogen production by agrivoltaics [127]); (ii) decarbonizing heating using heat pumps that are already economical in Canada [5], (iii) powering increased computing operations [78,128,129], and (iv) exporting electricity to the fossil fuel-dependent U.S. [130].

6. Energy Policy Recommendations

To capitalize on the benefits of agrivoltaics (see Figure 1) in Canada, three policy areas can be addressed: (i) research, (ii) regulations and standards, and (iii) incentives.

6.1. Support for Agrivoltaic Research in Canada

Provincial analysis of both Ontario [29] and Alberta [42] has shown great promise and substantial policy roadblocks for agrivoltaics. The wider potential for agrivoltaics shown in this study for all of Canada can be further improved by investigating the potential to convert all current pasture land to conventional solar farms with sheep, rabbits, or other grazing animals. In addition, these results can be further refined with GIS studies investigating the connection availability of the feeders and stations in various parts of each province, and then carefully determining the optimum deployment strategy while minimizing grid upgrades. This will initially provide a baseline for agrivoltaic land, using assumptions around available distribution connection capacity.

Substantial research is also needed in Canada to optimize PV systems for a wide array of agrivoltaics options. For all food crops currently farmed in Canada, the following PV system design aspects can be tested and optimized: (1) PV array geometry, type of racking for PV arrays, orientation of the array, spacing between rows of racks, and PV module types; (2) the type of tilting (including fixed-tilt—both vertical and sloped—variable tilt, single-axis and dual-axis tracking); (3) PV material and type including monofacial or bifacial modules, perovskite modules, organic PV-based modules, thin film modules, or silicon cell-based modules, (4) PV transparency (0–100%) as a function of light color, which can be adjusted by changing the cell packing densities of crystalline silicon-based cells or the thickness of thin film PV and/or light trapping/anti-reflective coatings; and (5) energy bandgap and, thus, spectrum of light converted from single or multiple bandgap materials.

There are several ways to increase the efficiency of agrivoltaics production even further. Progress has already been made in partially transparent and colored PV [131,132] and semitransparent PV modules used in greenhouses [133–136], and the technology can increase yields [51,137,138]. The spectral tuning of light with films and PV has been demonstrated to increase yields in a wide array of indoor spaces [139–145]. A large array of experiments needs to be conducted on agrivoltaics specialty modules on a range of conventional crops [88], aquaponics (aquavoltaics) for fish and water plants [146], and powering indoor vertical growing to increase food production further for the world's growing population.

Education and public awareness are also needed to disseminate the results of this research. One approach to doing this is to use citizen science [147,148] to provide information to consumers, farmers, and local communities considering deploying agrivoltaics. Furthermore, research that demonstrates the effectiveness and benefits of agrivoltaics should be made available to the public in an openly accessible format. It is suggested that the funding of such research projects be linked to open access requirements [149], as well as strategic open source requirements at the national scale [150], which will ensure that information is available to innovate as rapidly as possible and make informed decisions.

6.2. Agrivoltaic Regulations and Standards in Canada

Although most Canadians are unfamiliar with the concept of agrivoltaics, agrivoltaics social science in the U.S. indicates that the PV industry, farmers, and the general public will enthusiastically support it [151–153]. Agrivoltaics needs to be clearly define in Canada, to ensure that the agricultural benefits from PV deployment are realized. A tiered system for the categorization of agrivoltaic technology has been proposed on the basis of land utilization, as given below in Table 12 [29,42]. The more valuable tiers could be provided with greater incentives and obstacles to conventional 'dead' solar farms could be provided. In addition, agrivoltaics should be reserved for food crops and all incentives should be restricted for growing tobacco and other harmful drugs that negatively impact public health [154] instead of producing products that benefit people, such as food.

Table 12. Agrivoltaic systems tiers to favor greater land use efficiency and GHG emissions reduction potential. Adapted from [29].

Tier/Allowed Land Use	Agrivoltaic Type	Explanations
1. Prime agriculture	Crop	Refer to Section 2
2. Pasture	Grazing	Sheep [64,155], rabbits [156]
3. Marginal	Apiculture	Honey production [157]
4. Non-restricted	Beneficial Insect Habitat	Pollinators (e.g., butterflies), which provide services

Moreover, a technical guide or application standard should be developed to ensure proper implementation and best use of the technology. Documents such as Technical Guidance for Utility-Scale Solar Installation and Development on Agricultural, Forested, And Natural Lands [158], as well as Land Use Considerations for Large-Scale Solar [159], are helpful for farmers to make informed decisions when placing solar PV systems on farmland, including considerations related to construction and even decommissioning works. These can take the form of, for instance, soil sampling for ensuring the quality of soil before and after development works, timing for the PV development work and harvesting, ground topography to identify features of the site (wet areas, slopes, etc.) that impact solar deployment, management of invasive plants, techniques to minimize soil damage, road design features, erosion control strategies, best practices for trenching works, best practices for managing vegetation, and minimum requirements for decommissioning activities. The guidelines can also provide recommendations regarding design, installation, operation, and maintenance of agrivoltaics systems.

A detailed policy and regulatory review at both the federal and provincial level is necessary to reduce barriers to agrivoltaics adoption. One first step would be to define a standard for a specific methodology and best practices for the design, installation (important to preserve soil health), and testing/certification of agrivoltaic technology to ensure compliance to minimum standards for installation (e.g., minimizing impact on soil), operation, and maintenance requirements (e.g., minimizing use of additional herbicides).

6.3. Financial Incentives

The federal and provincial governments can incentivize rapid adoption of agrivoltaics technology through several mechanisms. Such incentives could be tax breaks for farmers willing to install agrivoltaics, such as reduced property taxes or exemption from sales taxes. Agrivoltaics could have access to Class 43.1 and 43.2 for renewable energy (i.e., access to accelerated depreciation [160]). As up-front capital for installation agrivoltaics can be a challenge, governments could provide easy and low- or no-interest loans. Additionally, governments could reimburse a portion of capital investments for installing agrivoltaics. Governments could also help accelerate agrivoltaics adoption with carbon credits, which could be traded and used to offset carbon taxes. Similarly, agrivoltaics could receive zoning benefits, feed in tariffs, or grants. Future work is needed to discern the most efficient approach. Canada can achieve sustainability and help achieve its climate- and renewable energy-related goals while tackling the ever-growing concerns of food and energy through the adoption of agrivoltaics.

7. Conclusions

This study estimated the agrivoltaics potential in Canada using a combination of GIS analysis over agricultural areas of individual provinces and SAM simulations for bifacial PV modules for single-axis tracking and vertical system configurations. Depending on the agrivoltaics technology employed, about a quarter to over one third of Canada's total electrical energy needs can be met by agrivoltaics alone using only 1% of agricultural land. These results show that agrivoltaics could be a major contributor to electricity generation and enable Canada to render the power generation sector free of GHG emissions. The fraction of agricultural land in each province that can be used to decarbonize the grid in the province is less than 1% for all provinces, with the exception of Alberta (1.4%), British Columbia (1.1%), and the Maritimes, which needs 4.1% using vertical agrivoltaics. If single-axis tracking were used, all provinces could be carbon-free with less than 1% of agricultural land dedicated to agrivoltaics, with the exception of the Maritimes (2.5%). All provinces other than Alberta, British Columbia, and the Maritimes need less than 0.5% of their agricultural land. Although a broad semi-quantitative analysis is presented in this study, and practical results might vary, it is clear that the potential of agrivoltaic-based solar energy production in Canada far outstrips current electric demand. Apart from making farming and electricity generation net zero in Canada, electricity generated from agrivoltaics can be used to decarbonize several sectors. First, agrivoltaics can provide electric vehicle charging and hydrogen production to decarbonize transportation in Canada. Second, it can be used to power heat pumps to decarbonize building heating. Third, agrivoltaic-generated electricity can be used to expand machine learning and AI applications, as well as cloud computing data centers, cryptocurrency miners, and servers in Canada to help accelerate economic opportunities. Finally, Canada can export green electricity to the U.S. to help Americans eliminate their dependence on fossil fuels. China and European countries are working aggressively to develop the technology and secure a competitive edge by leveraging agrivoltaics to improve agricultural economics. For Canada to remain internationally competitive and advance agrivoltaics technology on the commercial scale, policies are needed to support agrivoltaic research, define agrivoltaic standards, and modernize regulations. Further, by providing financial incentives and access to capital, agrivoltaics development in Canada can be accelerated to economically decarbonize the entire country.

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