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Review

Agrivoltaics in Ontario Canada: Promise and Policy

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Abstract: Well-intentioned regulations to protect Canada's most productive farmland restrict large-scale solar photovoltaic (PV) development. The recent innovation of agrivoltaics, which is the co-development of land for both PV and agriculture, makes these regulations obsolete. Burgeoning agrivoltaics research has shown agricultural benefits, including increased yield for a wide range of crops, plant protection from excess solar energy and hail, and improved water conservation, while maintaining agricultural employment and local food supplies. In addition, the renewable electricity generation decreases greenhouse gas emissions while increasing farm revenue. As Canada, and Ontario in particular, is at a strategic disadvantage in agriculture without agrivoltaics, this study investigates the policy changes necessary to capitalize on the benefits of using agrivoltaics in Ontario. Land-use policies in Ontario are reviewed. Then, three case studies (peppers, sweet corn, and winter wheat) are analysed for agrivoltaic potential in Ontario. These results are analysed in conjunction with potential policies that would continue to protect the green-belt of the Golden Horseshoe, while enabling agrivoltaics in Ontario. Four agrivoltaic policy areas are discussed: increased research and development, enhanced education/public awareness, mechanisms to support Canada's farmers converting to agrivoltaics, and using agrivoltaics as a potential source of trade surplus with the U.S.

Keywords: agriculture; agrivoltaic; Greater Golden Horseshoe; Canada; energy policy; farming; Ontario; photovoltaic; solar energy

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1. Introduction

Solar photovoltaic (PV) system costs have declined [1,2] to the point that solar electricity production is now normally the least costly electricity source, globally [3,4]. Throughout Canada, grid-connected PV systems are at grid-parity or beyond with the return on investment (ROI) of PV applications varying by province and utility [5]. PV can even be used to economically subsidize heat pumps to enable profitable electrification of gas-based heating in Ontario [6]. Unsurprisingly, PV electricity production in Canada continues to grow, although it makes up less than 1% of electricity generation, while Ontario is the dominant province for PV deployment with approximately 94% of Canada's total cumulative installed capacity [5].

Canadian PV growth is good for the environment as PV is a well-established, sustainable energy source [7], having been shown to be a net energy producer for the last 20 years [8]. Energy conversion efficiencies for PV have increased [9] to the point that the energy payback time is less than a year [10]. These benefits also come with challenges, such as the need for large land surface areas to power high-population-density cities, which are normally supplied by rural areas used for agricultural production [11]. Globally, most people live in cities [12]. For example, the four largest urban regions in Canada—Southern Vancouver Island, the Lower Mainland, the Calgary-Edmonton Corridor, and the Extended Golden Horseshoe—make up more than half (51%) of the population of Canada [13]. Siting conflicts over land use were once relegated to wind farm development [14–17] but are increasingly becoming a barrier to large-scale PV projects as residents worry about interference with agricultural production [18–21]. Globally, land-use conflicts would be expected to increase as population increases 1.15% per annum [22]. Food production must increase by 70% from 2005 to 2050 to feed the anticipated 9.1 billion people who will make up the global population [23], so understandably, decision makers do not want to make policies that decrease food production, in addition to protecting the pastoral legacy of Canada's rural areas. Past efforts to use food crop land for ethanol production increased global food costs and global hunger [24–27]. In Canada, the population growth rate is also changing constantly [28], and careful attention to protecting Ontario's croplands have been regulated [29,30]. A "Greenbelt" was established as a band of permanently protected territory in the Golden Horseshoe that maintains agriculture as the predominant land use and guards the agricultural land base from development [29–32]. These regulations, unfortunately, have some negative consequences, including increasing commuting distances [33], but also restricting the growth of the otherwise overwhelmingly environmentally beneficial solar PV deployment. In the past, the reasons against PV on farmland were clear. The Ontario Federation of Agriculture stated: " … large-scale solar on good farmland is not suited to Ontario. OFA believes solar development will cause erosion, bake the soil, disrupt carbon and nitrogen fixing, create habitat for weeds, and destroy habitat for many native creatures that share farmland. Large-scale solar on good farmland will not produce any more power than if it were located on rooftops or rocks and it will reduce farm production needlessly. OFA policy is to protect good farmland rather than using it for solar." [34]. Historically, this position made sense as converting an active farm to a close-packed industrial-scale solar PV system would be expected to decrease agricultural production to zero.

A growing number of studies, however, indicate that it is possible to have large scale PV development while protecting agricultural production using the new innovation of agrivoltaics—the strategic co-development of land for both PV electrical generation and agriculture [35–41]. Agrivoltaics provides several services, which are illustrated in Figure 1.

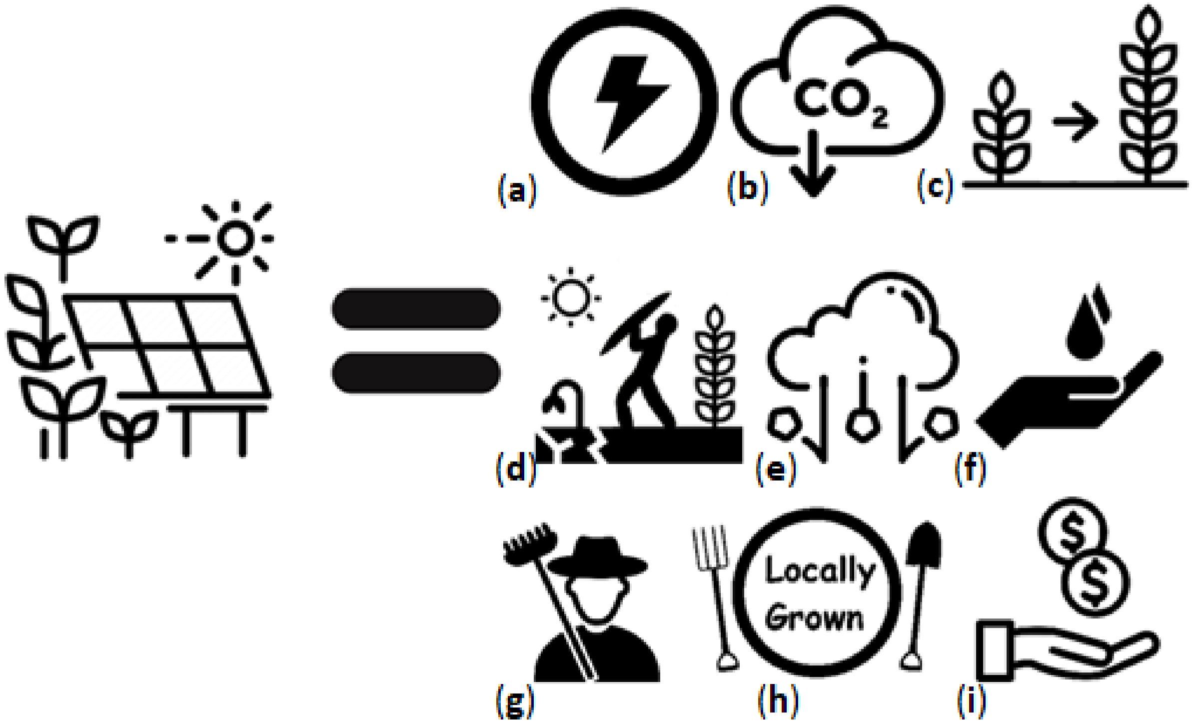

Figure 1. Services provided by agrivoltaics are denoted by the icons (**a**) renewable electricity generation, (**b**) decreased greenhouse gas emissions, (**c**) increased crop yield, (**d**) plant protection from excess solar energy, (**e**) plant protection from inclement weather, such as hail, (**f**) water conservation, (**g**) agricultural employment, (**h**) local food, and (**i**) increased revenue.

The first two outputs for agrivoltaics are well established as PV systems that produce renewable electricity, and this solar-generated electricity also decreases greenhouse gas

(GHG) emissions when it offsets fossil fuel-based electricity production [42]. Agrivoltaics also ensures that land remains productive during the winter by generating electricity year-round. Less intuitively, many studies show that agrivoltaics *increases* crop yield for a variety of crops [43–47]. Increased crop yield and the PV electrical production substantially increase land-use efficiency [48]. This is possible because agrivoltaics creates a microclimate beneath the PV modules that alters air temperature, relative humidity, wind speed, wind direction and soil moisture [49]. Agrivoltaics protects crops from both excess solar energy and inclement weather, such as hail, while also improving PV performance because of lower operating temperatures [35,45,50]. Thus, agrivoltaics have the potential to actually increase global land productivity by 35–73% [51], rather than decrease it, while minimizing agricultural displacement for energy [36,52]. Agrivoltaics also offers more efficient use of water, which promotes water conservation [53–56]. By maintaining the land for use in agriculture, employment of farmers remains intact, and these farmers provide local sources of food along with all the concomitant benefits [57–59]. Altogether, the solar energy and the increased land-use efficiency is worth money, and thus, increases revenue for a given acre for the farmer. The local community also benefits from protecting access to fresh food and renewable energy [37]. It should also be mentioned that advanced inverter management can also provide stability [60] to rural electric grids, which can improve power quality [61–63] and, if storage is implemented, create emergency islanded power grids that can reduce outage impacts [64,65].

Unfortunately, Canada is not yet on the forefront of agrivoltaics. There have been some notable demonstrations, such as Arnprior’s tri-part agrivoltaic system that houses a monarch butterfly conservation project, a bee/honey project, and a solar grazing/natural weed abatement pilot project [66]. Most Canadian agrivoltaics are primarily using conventional solar farms for grazing sheep, which does have positive benefits for both the sheep (i.e., protection [67] and higher quality grazing areas [68]), but also the PV systems (i.e., less labour for mowing) and the environment [69]. These lower-tier uses of agrivoltaics, however, leave out the majority of the potential agrivoltaic benefits. Other countries that make more aggressive use of agrivoltaics will generate more revenue per acre and win competitive markets.

Canada, in general, and Ontario in particular, is at a strategic disadvantage in the agricultural space without the use of agrivoltaics. The objective of this study is to investigate the policy changes necessary to capitalize on the benefits of using agrivoltaics in Ontario. First, the background on land-use policy in Ontario will be reviewed in the context of the renewable energy policy. Second, three short case studies of current Ontario crops (peppers, sweet corn, and winter wheat) will be analysed for the potential agrivoltaic boost to both crop production and solar energy generation. Third, these results will be discussed in conjunction with potential policies that would continue to protect the greenbelt of the Golden Horseshoe, while enabling and encouraging agrivoltaics in Ontario.

2. Methods

In Section 3, the background on Ontario’s land-use policy will be reviewed in the context of the renewable energy policy. After comparing the peer-reviewed literature for experimental agrivoltaic research of crops that showed an increase in yield with the list of crops in Ontario [70], three crops were selected. These crops were selected to have a variety of traditional shade tolerances, as well as covering both vegetables and grains. First, peppers prefer direct sunlight in general, but pepper plants may still be grown in partial shade. This was shown to be beneficial with agrivoltaics, as several varieties of peppers have shown an increase in yield under PV in a U.S. study [45]. Next, corn was selected as a crop that generally prefers full sun, and a recent study in Japan found increased sweet corn yields with agrivoltaics [47]. Finally, winter wheat was selected as a grain crop, and a German team recently showed increased yields with agrivoltaics [48]. The analysis is run under the assumption that all the agricultural land currently dedicated to each crop is converted to an agrivoltaic system growing the same crop in the same area.

The potential estimated additional (A) crop yield of each type in Ontario is estimated by:

$$A_c = P_c y_c [\text{lbs}] \tag{1}$$

where P_c is the market production in Ontario [70] in lbs and y is the yield increase in percent from experimental measurements in the literature [45,47,48], and the c subscript is for the crops of peppers, sweet corn, and winter wheat, respectively. The value (V) of these crops is given by:

$$V_c = A_c m_c [\text{CAD}] \tag{2}$$

where m_c is the market value of the crop in Canadian dollars per pound, which was determined in the sources [70,71], and a sensitivity on the market value of wheat [72], respectively.

The potential solar power (S) for converting these crop areas over to agrivoltaics is given by:

$$S_c = a_c f [\text{kW}] \tag{3}$$

where f is the packing factor (kW/acre), and a_c is the area for a given crop c under cultivation, measured in acres is provided by the Ontario Ministry of Agriculture, Food and Rural Affairs [70,71] and the PV systems are modelled in two cases. The first, the high packing factor case, is conservatively assumed to be 314 kW/acre following Lytle et al. [73] in the U.S. but using partially transparent modules and closer packing. The second case is the low-packing factor case of 228 kW/acre for following Trommsdorff et al. [48], which was experimentally verified on high-mounted, sparsely populated racks for the wheat case in Germany. Finally, the energy yield for PV systems of S for each crop's agrivoltaic system is simulated in SAM [74] using the basic PVWatts model, assuming a fixed tilt at 30 degrees (high packing factor case) and 20 degrees (low packing factor case), facing due south and the solar flux for Orangeville, ON. The DC to AC size ratio was 1.2, inverter efficiency was 96%, with a total loss of 13.2% comprised of 2% soiling losses, 3% snow losses, mismatch and wiring losses of 2% each, connections of 0.5%, light induced degradation of 0.5%, and availability of 3%. Finally, a sensitivity is applied to the output solar energy (kWh) by the cost of electricity, which was again conservatively estimated as the low ($0.0037/kWh) and high ($0.0271/kWh) monthly wholesale electricity prices reported by the IESO [75].

3. Background on Ontario Land-Use Policy

3.1. Governance

Canada's national government operates as a federal democracy as well as a constitutional monarchy. Each provincial or territorial government has a distinct legislature that oversees local matters and controls municipalities within its jurisdiction. Within the province of Ontario, municipalities are subject to a style of legislation known as "laundry list", in which the powers that are not explicitly stated or implied by the provincial legislature are not granted [76]. This is relatively restrictive. In the context of renewable energy development and agricultural land use, Ontario has made clear the rights of its municipalities through several policy documents, described below.

3.2. Agricultural Heritage

Ontario is in the heart of the Great Lakes region and possesses the most productive farmland in the country within the semicircle of area surrounding Lake Ontario. This area, known as the Greater Golden Horseshoe (GGH) [77], is highlighted in Figure 2. Fertile soils, abundant water resources, and a temperate climate coalesce to position the GGH as a leader in diverse and bountiful agricultural production. Within the GGH, the "Greenbelt" has been established as a band of permanently protected territory that maintains agriculture as the predominant land use and guards the agricultural land base from development. To uphold the agricultural legacy and the viability of the agri-food sector in Ontario, the province has developed a set of some of the most protective land-use policies in the world.

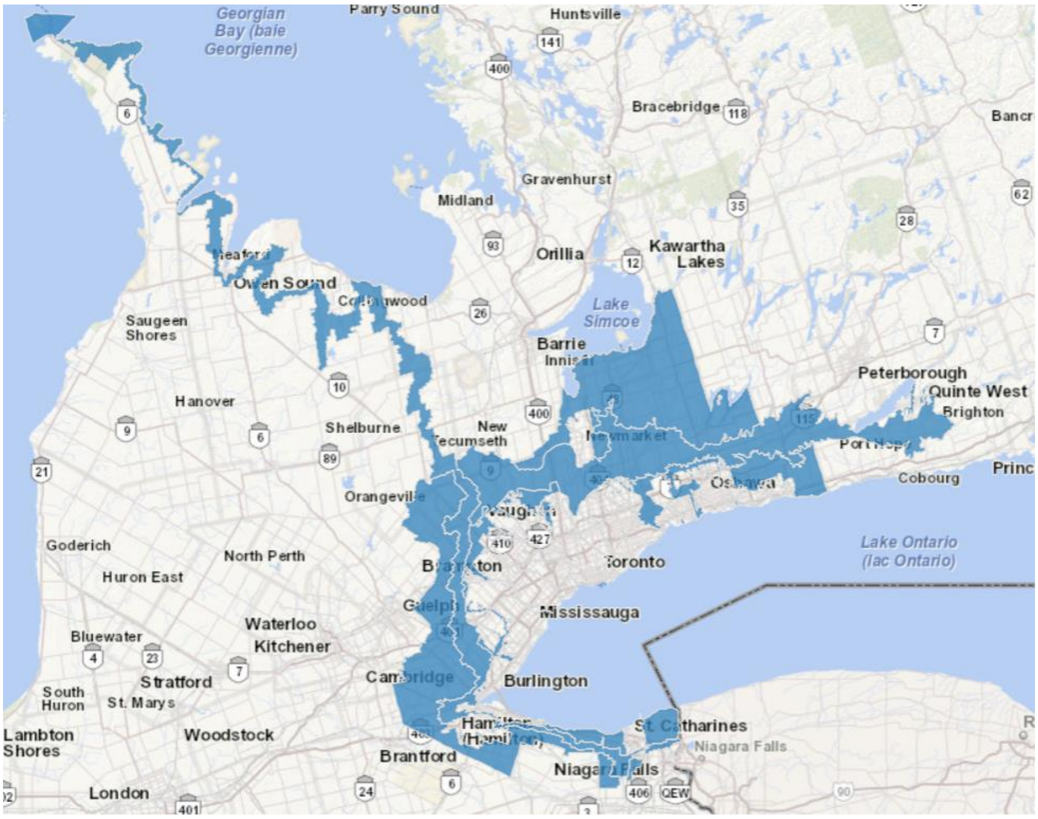

Figure 2. Land classified as green belt in Ontario [77].

3.3. Land Use Policy in the Greenbelt

The Provincial Policy Statement (PPS) (2020) lays the policy foundation for regulating the use and development of land in Ontario [78]. All subsequent ecological protection plans are built upon the PPS, including the Growth Plan for the GGH (2020), and the Greenbelt Plan (2017), which together form a provincial level fortress that protects agricultural land from development that may threaten continued use of the land for farming [79,80]. Municipal governments are tasked with further refining these sets of policies by generating place-based land designations, including prime agricultural areas and specialty crop areas in an "Official Plan". These plans must contain related criteria for permitted uses in these designated areas; the municipal level is thus the critical leverage point for agrivoltaic development.

3.4. Renewable Energy Policy

Being the first province in Canada to implement the feed-in tariff model through the Green Energy Act (2009), Ontario is the leader in solar energy in Canada [81]. Despite this leadership role within Canada, solar electricity still makes up less than 1% of electricity generation as shown in Figure 3. Part of this lack of PV capacity is that although province-wide criteria are imposed as minimum standards upon solar developments, these are followed by municipal-level standards that are often more stringent and place-based.

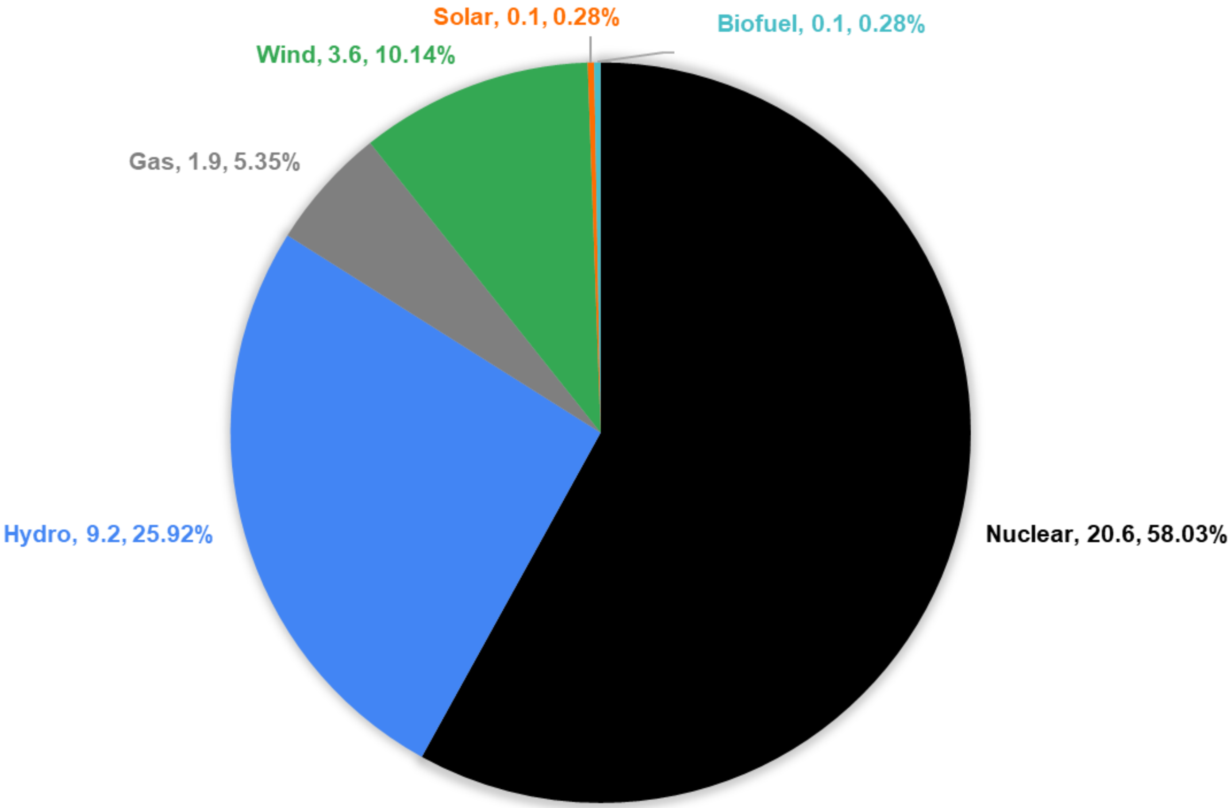

Figure 3. Electricity mix in Ontario [82].

3.5. The Intersection of Agriculture and Solar Energy in Ontario

Ontario's three-tiered land-use policies define what types of uses are allowed on prime agricultural lands, specialty crop areas, and rural areas. A full range of uses are permitted—particularly uses that increase income, diversify the tax base, and create employment opportunity—if specific criteria are met. Uses on these designated lands are organized under three categories: (1) agricultural, (2) agricultural-related, and (3) on-farm diversified [83].

Any proposed infrastructure that intersects these designated lands is subject to an agricultural impact assessment [80]. Renewable energy facilities are subject to the Green Energy Act (2009), rather than the Planning Act (1990), and therefore obtain approval under the REA rather than the PPS [84], while adhering to municipal land-use criteria. For solar photovoltaics, these rules are particularly restrictive currently, as the Provincial Policy Statement of 2020 states, "Ground-mounted solar facilities are permitted in prime agricultural areas and specialty crop areas only as on-farm diversified uses." [78]. The intention of an "on-farm diversified use" is to diversify income for farmers through a secondary, compatible, *limited* use of the land. To qualify as on-farm diversified use in designated agricultural land, all uses (including a ground-mounted solar PV) must meet the following condensed list of key criteria [83]:

- Is related to, and can coexist with, agricultural operation
- Must not impair, inconvenience, or undermine surrounding agricultural operation
- Be located on a farm actively in production and be *limited in an area based on a lot coverage ratio basis (emphasis added)*
- Meet all applicable provincial air emission, noise, water, and wastewater standards and receive all relevant environmental approvals
- *Be secondary to the principal use of the property (agriculture), which is measured in spatial and temporal terms* (the following temporal considerations apply to uses that are temporary):

- Does not require site grading and/or drainage unless it improves conditions for agricultural production
- Impacts to the site and agricultural operations are mitigated (e.g., compaction, drainage, trespassing)
- A harvestable crop is produced on the land the year in which the temporary use is implemented

This is heavily restrictive to PV farms without considering agrivoltaics.

4. Results and Discussion

Assuming that all the field crops were converted to agrivoltaic systems in Ontario for peppers, sweet corn, and winter wheat, considerable amounts of food and additional revenue would be created, as shown in Table 1.

Table 1. Estimated additional yield and crop values for agrivolataic-enhanced crop potential in Ontario for peppers, sweet corn, and winter wheat.

Crop	Marketed Production ('000 lbs)	Average Price (Cents/lb)	Additional Yield ('000 lbs)	Additional Agrivoltaic Crop Value
Peppers	87,960	33.7	154,810	$52,170,835
Sweet Corn	216,958	15.4	10,150	$1,563,113
Winter Wheat (low value)	4,818,000	6.7	144,540	$9,684,180
Winter Wheat (high value)	4,818,000	15.8	144,540	$22,837,320

Peppers would see the largest potential yield gain, which is worth $52 million annually. This value must be used with caution, as the calculation is extrapolated from substantial gains observed for agrivoltaics growing chiltepin peppers in Arizona (native to the U.S.). Since agrivoltaics' water conservation and excess solar shielding properties are robust, it may have been particularly useful in Arizona to increase pepper yields, whereas in Ontario, this may or may not be the case. Other peppers could have different gains and the gains would be expected to vary with weather conditions and location, just as is normally observed with agriculture. An additional $1.5 million of sweet corn could be produced from the approximate 4.7% yield increase observed in Japan if agrivoltaics were used on Ontario's sweet corn crop. Finally, Ontario's winter wheat crop may produce between $9.6 million and $22.8 million in value if the same increase in crop yields is found as those reported in Germany. The value of agrivoltaic crop production increases is highly volatile because the cost of food commodities is highly volatile. This is best illustrated with the winter wheat case study, as wheat prices are highly unstable, as shown in Figure 4. Agrivoltaics provides farmers with a steady, predictable revenue stream from electricity that helps dampen the risk of such volatility.

In summary, the specific economic values shown in Table 1 must be considered to only be illustrative estimates, as they are derived from agrivoltaic yields compared to control crops in countries outside of Canada. In addition, the volatility in food crop prices is larger in percent than the percent increases generally expected for agrivoltaics. Even with these limitations in mind, it is clear from the results in Table 1, if only considering the agricultural services of agrivoltaics to increase yield, it is an extremely promising opportunity for Ontario.

The potential value from the solar electricity generated from the conversion of field crops in Ontario for peppers, sweet corn, and winter wheat also has considerable variance. This variance is caused by two fundamental variables: (1) the packing factor measured in kW/acre for the PV modules and (2) the value of the generated electricity. The former is a complicated geometric combination of both the light transmission value of the PV modules (agrivoltaic modules can be monofacial, bifacial, and partially transparent for both modalities, which all have an impact on the power of a module), as well as the array geometry and spacing between both rows and modules within a row. To investigate the sensitivity of the packing factor, two cases are considered: the first, at 314 kW/acre, would be viewed as a reasonable value for a conventional agrivoltaic system, while the value of 228 kW/acre is what has been experimentally tested for large-area, grain-based agrivoltaic production. This large variance is seen in the results for the high and low packing factor agrivoltaic cases of additional PV-generated electricity for Ontario per year shown in Tables 2 and 3, respectively. The corn and wheat are probably closer to the optimum performance for the crop using the lower values in Figure 4, which indicates that, if all of Ontario's farmland currently growing sweet corn and winter wheat were converted to agrivoltaics, additional electricity revenue (most likely coming from the sale of wholesale electricity to the U.S.) would account for between $1.02–$7.48 billion/year in revenue. In the case of the peppers, the packing factor shown in Table 2 is likely more appropriate, providing between $5.8–$42.7 million in additional solar electric revenue per year from the fields currently growing peppers in Ontario. By comparing the value of the additional crop revenue (Table 1) and the solar electric revenue (Tables 2 and 3), it is not surprising that the latter is much higher because the values in Table 1 are only the increases, not the overall revenue from crop farming the same area.

Figure 4. Volatile wheat prices ($/bu) over the last decade.

Table 2. High-packing factor agrivoltaic case of additional PV-generated electricity for Ontario per year.

Crop	Area Harvested (Acres)	Additional PV Power (kW)	Additional Energy (kW-hrs/Year)	Low Value ($0.0037/kWh)	High Value ($0.0271/kWh)
Peppers	3808	1,195,712	1.58×10^{9}	$5,835,433	$42,740,606
Sweet Corn	21,834	6,855,876	9.04×10^{9}	$33,458,732	$245,062,602
Winter Wheat	920,000	288,880,000	3.81×10^{11}	$1,409,821,064	$10,325,986,712

As can be seen in both Tables 2 and 3, the value of electricity covers a wide range, even when considering only using the extremely conservative average monthly wholesale rates for the electricity values. Retail rates of electricity can increase the value of even the high rate used in the Tables by a factor of 10, and on-peak rates (generally during the summer when caused by high temperatures and widespread air conditioner use when PV production is highest) are much higher than that. The results presented in Tables 2 and 3 are thus illustrative of the rough minimum value of the solar electricity that would be generated by the agrivoltaic systems. Determining the exact value of the electricity potentially generated from such agrivoltaic systems is far beyond the scope of this study, as it would entail not only geographic considerations for the technical aspects (e.g., horizon shading and latitude changes throughout Ontario), but also economic ones that would vary with, for example, the year, the penetration rate of solar, the value of offsetting GHG emissions, etc. Overall, the value of solar (VOS) is a complex topic [85,86] that needs to be calculated for each specific case and is left for future work. In addition, the values shown here do not include the second order effects (e.g., agrivoltaic systems operate cooler than conventional solar farms, which provides about a 1% increase in PV output annually). Overall, the combination of the values in Table 1 with either those in Table 2 or 3 are a promising source of additional revenue for farms in Ontario.

Table 3. Low-packing factor agrivoltaic case of additional PV-generated electricity for Ontario per year.

Crop	Area Harvested (Acres)	Additional PV (kW)	Additional Energy (kW-hrs/Year)	Low Value ($0.0037/kWh)	High Value ($0.0271/kWh)
Peppers	3808	868,224	1.12×10^9	$4,131,183	$30,258,127
Sweet Corn	21,834	4,978,152	6.40×10^9	$23,687,043	$173,491,584
Winter Wheat	920,000	209,760,000	2.70×10^{11}	$998,080,032	$7,310,261,856

5. Policy Recommendations

Agrivoltaics should be considered an agricultural use or agricultural-related use due to its positive impact on agricultural production and solar PV electricity production. The light management that agrivoltaics provides (especially for greenhouse-integrated photovoltaic (GiPV) [87]) that leads to yield increase should be considered equivalent to the use of crop rotation strategies, or to water and nutrient management practices.

Table 4 outlines Ontario's province-wide criteria [83] for use of prime agricultural lands, which are more acutely defined at the municipal level, and then considers agrivoltaic as well as conventional solar farm acceptability. As can be seen in Table 4, agrivoltaics meet these requirements while conventional PV farms do not.

Table 4. Conventional solar farm and agrivoltaics matches to criteria for permitted uses in prime agricultural areas in Ontario.

Criteria for Permitted Uses in Prime Agricultural Areas	Conventional PV Farm	Agrivoltaics
1. Farm-related commercial and farm-related industrial uses	No	Yes Agriculture continues
2. Shall be compatible with and shall not hinder surrounding agricultural operations	No	Yes Benefits Agricultural
3. Directly related to farm operations in the area	No	Yes Agriculture continues
4. Supports agriculture	No	Yes Yield increase, water conservation, and plant protection
5. Provides direct products and/or services to farm operations as a primary activity	Yes, if some power goes to farm	Yes Yield increase, must be considered holistically
6. Benefits from being in close proximity to farm operations	No	Yes Lower PV operating temperatures

A second path to adding PV infrastructure on agricultural land in Ontario is to utilize the rules for on-farm diversified criteria summarized in Table 5 for conventional PV farms as well as agrivoltaics. In this case, the interpretation enables some PV systems to be built, particularly if the area is limited. This limited area requirement does not appear to make sense in the agrivoltaic context. If agrivoltaics are improving the agricultural production of a farm, as well as the economics and environmental impact, the area for which it is utilized should be maximized instead of restricting it.

Table 5. Conventional solar farm and agrivoltaics matches to criteria permitted for on-farm diversified uses in prime agricultural areas in Ontario.

On-Farm Diversified	Conventional PV Farm	Agrivoltaics
1. Located on a farm	Yes	Yes
2. Secondary to the principal agricultural use of the property	Maybe	Yes holistically
3. Limited in area	Unclear	Unclear
4. Includes, but is not limited to, home occupations, home industries, agri-tourism uses, and uses that produce value-added agricultural products	No	Yes
5. Shall be compatible with, and shall not hinder, surrounding agricultural operations	Yes	Yes

Rather than outright bar the use of large-scale PV on farms, given the numerous benefits (Figure 1) to farmers, including the potential to increase agricultural output, it would appear rational to consider encouraging agrivoltaics in Ontario and the rest of Canada. This is perhaps made even clearer by the fact that nearly all the experimental agrivoltaic research is made outside of Canada in nations that will quickly have a competitive agricultural advantage if they deploy agrivoltaics at scale. As the results show in Tables 1–3, these advantages have real economic consequences that could leave Ontario's farmers uncompetitive without them.

While maintaining the land base for agriculture is paramount, another important objective of Ontario's land-use policy is supporting the growth of the rural economy. Historically, when energy development is proposed that offsets food production on agricultural land while also providing rural economic opportunity, a land use conflict arises between competing objectives. Agrivoltaic development solves this problem in general and can solve this issue in Ontario. There are four primary policy areas involving agrivoltaics in Ontario and Canada that need attention in order for this to occur: (1) research and development, (2) education/public awareness, (3) policy mechanisms to support farmers, and (4) utilize agrivoltaics as a potential source of trade surplus with the U.S.

5.1. Support-Applied Agrivoltaic Research in Ontario

First, the results of this analysis make it clear that agrivoltaic research in Ontario should be supported. This work should first concentrate on Ontario's major markets for agriculture. This not only includes the crops that have more than 10,000 acres devoted to them in Ontario (e.g., sweet corn with 21,834 acres used as a case study here, green peas with 15,507 acres, tomatoes with 15,223 acres, and green/wax beans with 10,208 acres), but also the dozens of other vegetables and specialty crops [70]. In addition, agrivoltaic research should be performed to consider including the more than 2.1 million acres of grain corn and over 3 million acres of soybeans as well as other grains and dried beans [71].

Agrivoltaics is under intense research in other parts of the world, but to date only a handful of crops have been investigated, including aloe vera [88], aquaponics (aquavoltaics) [89], basil and spinach [90], celeriac [91], chiltepin peppers, jalapenos, cherry tomatoes [45], sweet corn/maize [47,92], grapes [93], kale, chard, broccoli, peppers, tomatoes and spinach [46], lettuce [43,53], pasture grass [49], potato, celeriac, clover grass, winter wheat [48], and wheat [35,94]. In general, these studies showed either marginal impacts on crop production or an increase for low density shading from agrivoltaics. Increases were seen primarily with shade tolerant crops and leafy vegetables, such as lettuce, that prefer partial shading from PV to prevent bolting and increasing growth time. Decreases, however, were observed for heavy shading from close-packed non-transparent PV.

To guide agrivoltaic design, Riaz et al. introduced the light productivity factor, which can be used to start evaluating the effectiveness of irradiance sharing for specific crop types based on its effective photosynthetically active radiation (PAR) and PV array design [95]. Agrivoltaic research and optimization is far from complete. Most studies to date have focused on a single crop (or a few) and tested one basic geometry of the PV systems in one location. There is far more research needed as there are dozens of crops commercialized in Ontario and over 20,000 species of edible plants [96]. In addition, PV system designs can impact agrivoltaic production, including the following variables:

(i) array geometry, orientation, and type of racking [97]
(ii) fixed-tilt, single-axis, or dual-axis tracking
(iii) type of module (size, monofacial vs. bifacial, uniform, similar to thin film modules, or non-uniform transmission from silicon cell-based PV technology)
(iv) type of PV material that constitutes the module (e.g., single bandgap, bandgap value, or multiple bandgaps)
(v) transparency of module
(vi) spectral transmission of module including the impact of optical enhancement techniques, such as anti-reflection coatings (ARCs) (i.e., partially transparent coloured PV) are under investigation for windows [98,99] that could also be useful for agrivoltaics. Semi-transparent PV has already been integrated into greenhouses [99–103] and tinted semi-transparent PV [104] can actually increase yields for some plants [90]).
(vii) the use of spectral shifting materials within the module if the agrivoltaic system is in an open field or enclosed in a greenhouse. Such spectral shifting materials are being investigated for use in greenhouses to make the light more beneficial for plant growth [105–107] and increase greenhouse production [108].

The potential permutations need to be optimized for Ontario and its crops, which represent an enormous amount of experimentation. New agrivoltaic systems need to be tested and optimized for compatibility with target crops and their associated operations (e.g., soil management, fertilization, sowing, irrigation, and harvesting, as well as dust generation during these agricultural operations). For example, greenhouse solar panels [109] could be optimized for specific crops by altering the transparency by the spacing of cells in a module. Doing this one commercial greenhouse [110,111] at a time, per crop, would be both expensive and time consuming for even one given module. This, however, becomes completely prohibitive once module experimentation is also considered. For example, 'red greenhouse modules' themselves needed to be optimized (e.g., testing the density, size, and chemical makeup of nanoparticles responsible for the spectral shifting via fluorescence [112–114]). They also need to be tested both for field use as well as greenhouse use. Innovation is already happening regarding this in Ontario [87]. Enabling agrivoltaics could drive additional local innovation development and job growth. Agrivoltaics would thus benefit from coordination and partnering between funders focused on energy (e.g., The Office of Energy Research and Development (OERD)) and agriculture (e.g., The Agricultural Research Institute of Ontario and the Ministry of Agriculture, Food, and Rural Affairs in Ontario).

5.2. Increase Public Awareness of Agrivoltaics in Ontario

To overcome these challenges related to the vast quantity of research needed in agrivoltaics, a parametric open-source cold-frame agrivoltaic system (POSCAS) was proposed to make low-cost agrivoltaic testing systems work in one single-module mini greenhouse at a time [115]. These devices could be used at a research station to test many variables at once. More importantly, these devices could also be used to foster public awareness of agrivoltaics using the approach of citizen science [116,117]. By enabling citizens to investigate the large number of permutations of PV designs and crops, two problems will be solved simultaneously. Such an enterprise could first, for example, target the help of master gardeners to quickly screen local produce for benefits for agrivoltaics by providing them with a free POSCAS and open-source, collaborative, well-structured, online research reporting. This would minimize R&D costs while also educating the wider population about the benefits of agrivoltaics.

Most North Americans are simply unaware of agrivoltaics, but when exposed to the idea they are in support of it [118]. Citizen science, similar to that described above, may help in part with public awareness, but broad, openly-accessible demonstrations are needed to verify the viability of the agrivoltaic approach in Ontario and to inform policymakers as well as build public trust. After preliminary experimental Ontario-based agrivoltaic studies indicate promise, open pilot studies should be conducted to allow farmers and citizens free access to the results. Opening rural lands to agrivoltaic R&D and demonstration can also prevent other types of proposed development on prime agricultural lands, while ramping up education on agrivoltaics in the province.

5.3. Streamlined Agrivoltaic System Deployment and Regulation

Given the modest agrivoltaic presence in Canada currently, in addition to more R&D and public education, there exists a need for an explicit definition and classification of agrivoltaic systems for regulation purposes. Agrivoltaics transcend traditional photovoltaic development by allowing continued use of the farmland beneath the array and is therefore uniquely positioned to enable the prosperity of agricultural producers and the diversification of their income, while stimulating rural economic growth through the generation of low-carbon electricity from sunlight. A proper definition is needed to acknowledge that agrivoltaics will not disrupt the geographic continuity of the agricultural land base. To prevent abuse of agrivoltaic-friendly regulations, it may be useful to divide agrivoltaics up into tiers, as is shown in Table 6. Tier 1 agrivoltaic solutions would be preferred and incentivized over Tier 2, etc. Such a tiered system would, for example, prevent a solar developer from simply seeding a conventional PV farm with wildflowers to acquire access to prime agricultural land.

Ontario can look to other jurisdictions, such as Japan, the U.S. and Europe, for examples of effective agrivoltaic policy. In Japan, agrivoltaic development exploded after the introduction of feed-in tariff (FIT) in 2012 [119]. Tajima and Iida found that the FIT was significantly more effective than a renewable portfolio standard (RPS) system previously used in Japan and that agrivoltaics is expected to play a major role in revitalizing Japanese agriculture, including reclamation of abandoned farmland [119]. Canada thus has the opportunity to reintroduce a FIT targeted specifically on agrivoltaics, and Ontario already has experience in this domain with the Green Energy Act. Perhaps even more targeted, the Massachusetts Department of Energy Resources established the Solar Massachusetts Renewable Target (SMART) program that regulates and provides incentives for PV, and agrivoltaics in particular [120–122]. The economics of PV are profitable in Ontario, but could be strengthened, and a program could help overcome other barriers, including access to low-interest capital and streamlining the process with utilities and other sources of bureaucracy. In Europe, a standard has been developed as a test method for agrivoltaic systems that provides a uniform way to report agrivoltaic measurement figures for legislative and funding bodies and the approval authorities, as well as for the post-testing and certification of agrivoltaic systems by experts and certification organizations [123]. Canada, in general, and Ontario specifically, could build upon and improve upon these standards to ensure they remain open access and thus freely available to all Ontario’s farmers.

Table 6. Potential tiers of agrivoltaic systems to favour systems with greater land-use efficiency and greater potential for GHG emissions reductions.

Tier/Allowed Land Use	Agrivoltaic Type	Comments
1. Prime agriculture	Crop	See Section 5.1 for crops investigated to date
2. Pasture	Grazing	Sheep [51,124], and rabbits [73]
3. Marginal	Apiculture (beekeeping)	Honey production [125]
4. Non-restricted	Insect Habitat	Pollinators, e.g., butterflies, that provide secondary services

Thus, a legal recognition of agrivoltaics as an agriculture-related use, or an on-farm diversified use (see Tables 4 and 5), by the province of Ontario and the relevant municipal permitting systems could help overcome the current barriers to PV development embedded in the regulatory process. Authorizing agrivoltaics on prime agricultural land through either of these land-use classifications will generate a distinct development opportunity for Ontario. Thus, agrivoltaic growth will be directed to uphold the economic, social, and environmental aims of the province's land-use policies without compromising the quality of agricultural land for future generations.

Finally, to increase agrivoltaic deployment velocity in Ontario, provincial and municipal policies should be aligned. Policy related to energy development and agricultural land-use in Ontario at both the provincial and municipal levels are robust, yet the regimes are stratified and siloed, which also complicates the realization of agrivoltaic systems. To minimize incompatibility between renewable energy and farmland preservation goals, provisions are needed that clearly address the overlap between the siting of energy systems on farmland which maintain the existing land use (i.e., agrivoltaics). The current policy language does not account for solar PV systems that retain the agricultural function of the land; this omission, while likely unintended (as agrivoltaics is a relatively new field), stops the potential for dual-use system development. Finally, provincial energy policy could incentivize agrivoltaics, followed by special municipal-level criteria for the siting and design of systems. Aligning energy policy regimes with place-based land use regulations would create a supportive policy landscape for the development of agrivoltaics in Ontario.

5.4. Treating Agrivoltaics in Ontario as a Potential Source of Trade Surplus with the U.S.

Ontario will need to develop a new generation capacity to displace the loss of nuclear generation when the Pickering nuclear generation station (15% of Ontario's total) retires in 2024. As well, there is expected to be significant growth in electric demand from electric vehicles and heating electrification growth, along with increased demand from a greater population with current immigration targets. Ontario is already fairly advanced in terms of low-carbon electricity generation and has closed its coal plants. As can be seen in Figure 3, very little of Ontario's current electricity production is a large source of GHG emissions, however, international power lines currently connect Canada to the U.S. Ontario has interconnections with Manitoba and Quebec in Canada, and with Michigan, Minnesota, and New York in the U.S. This provides Ontario the opportunity to offset emissions with low carbon power from agrivoltaics in the Eastern U.S. (Maine, New Hampshire, Vermont, New York, and Massachusetts), the U.S. West (Washington and Montana), and the U.S. Midwest (North Dakota, Minnesota, and Michigan). The U.S. interest in Ontario's electricity stems in part from renewable portfolio standards (RPS) and renewable electricity targets in many U.S. states, which mandate minimum levels of renewable power in each state's electricity mix, and often do not distinguish between domestic and imported renewable power. As many U.S. states have abysmal carbon emissions [126], Ontario's exports of renewable solar power to the U.S. are well-positioned to grow [127].

This is because, as of 2018, about 96% of electricity generated in Ontario was produced from zero-carbon emitting sources [128]. The U.S. is less fortunate [129], with over half of its electricity produced by coal-fired power plants that are directly responsible for more than 50,000 premature American deaths per year from the coal-fired power plant-related air pollution [130]. Agrivoltaics in Ontario has the promise to reduce this American coal-fired pollution-related death toll at a provincial profit. It should also be noted that American coal-fired air pollution unquestionably invades Canada from the southern border and causes premature Canadian morbidity and mortality costs as well, but as of yet, has not been adequately quantified. Agrivoltaics in Ontario could end these negative impacts on Canada's economy while also making a profit. For example, if experimental results in Ontario's grain corn acreage was to have similar results to that of Japan's sweet corn acreage, and is converted to agrivoltaics, this would provide an area to install over 478 GW of PV, which would be expected to produce roughly 6.16×10^{11} kWhrs/year (616 TWhrs/year). To put this in perspective, this is an order of magnitude higher than Ontario's current capacity and could offset 16.8% of all of the U.S.'s electrical consumption [126]. This result is consistent with previous work that found that constructing agrivoltaics on less than 1% of the world's cropland is enough to generate electricity for the entire planet [52]. Similarly, PV power of 40–70 GW would be possible if lettuce cultivation alone were converted to agrivoltaic systems in the U.S. [37], but the U.S. faces a politically fractured policy landscape. Thus, for Ontario to take advantage of this opportunity, it needs to move more quickly at modernizing land-use regulations before the U.S. makes moves to do the same. While this is the theoretical potential increase in Ontario's solar PV capacity, additional large-scale transmission development to deliver excess energy to the U.S. is required, which will have a land-use impact. Future research is needed to quantify the technical requirements, costs, and ROI of this approach as well as expand them to all the potential crops across Canada [131,132].

5.5. Limitations

Despite the many benefits of agrivoltaics, there are some limitations and drawbacks. A small amount of surface area is lost to cultivation (e.g., the surface areas of the racking/ground interface), but in general, this is made up for by the higher yields per unit total area of the agrivoltaic farm. Farmers also may need to adapt their procedures for working around the modules to prevent debris from shading the PV or breaking it. This may take more time or add additional costs. These costs need to be quantified for all the experimental work outlined above. In addition to the vast quantity of experimental work that was discussed above, which is needed to optimize agrivoltaic systems for specific crops, most farms rotate crops to sustain soils [133]. Farmers must make complex decisions on crop selection, spatial distribution within their farms, and temporal successions over the years [133]. Making optimal decisions becomes even more complicated with agrivoltaics, as only a handful of studies have looked at crop rotation and agrivoltaics. Moreda et al. [134] have studied (theoretically) rotating 9 types of crops in the southwest of Spain, Weselek et al. [91] have investigated a 4-year rotation cycle, and Trommsdorff et al. [48] looked at a crop rotation scheme including potato, celeriac, clover grass, and winter wheat. Thus, the agrivoltaic experimentation necessary to provide the data to make a large-scale transition to agrivoltaics needs to be run over multiple years with varying crops. Considering potential crop rotations, the optimum agrivoltaic systems may be dynamic both in terms of geometry and spectral properties. This, again, is an area of needed future research, and a lack of current data causes uncertainty for decision makers. In addition to these operational drawbacks and limitations of knowledge, there are also some drawbacks to the wide-scale adoption of agrivoltaics. The most obvious are those based on capital. From an agricultural perspective, the use of agrivoltaics increases the capital cost per acre far more than what conventional farming costs. Similarly, because of the increased spacing and the semi-transparent PV modules used in agrivoltaics, the density of power (W/acre) would be lower, and the capital cost ($/W) of an agrivoltaic system would be expected to be higher than a conventional utility scale solar PV system. The overall revenue each year per unit acre or per unit capital invested in the PV systems can be much higher for agrivoltaics to make up for these initial costs, but some means of financing with sustainable business models are needed to enable agrivoltaics to scale. These could be in part based on improvements in hail insurance, which needs to be quantified in future work. Even when policies are enacted to assist in this scaling though, there are other challenges to having large-scale agrivoltaic systems dispersed in large power volumes, which are the same issues involved with massive integration of PV [135], such as voltage fluctuations, power quality issues, dynamic stability, big data challenges [136], overvoltage, and reverse power flow [137]. High PV penetration on an already mostly green Ontario grid with agrivoltaics indicates that for optimal climate change mitigation, much of the solar power would need to flow to the U.S. to offset their more-polluting power sources. This cross-border electricity trading can bring political challenges, as some Americans ascribe to domestic energy independence, regardless of the environmental and economic costs [138]. High penetration rates can also be overcome, in part, by building more storage and flexibility into the demand for electricity (e.g., with electric vehicles [139–141]). Finally, a high penetration rate of agrivoltaics will change the view of the landscape, and this may make further build out socially challenging. Initial survey results in the U.S. indicate relatively widespread social acceptance of agrivoltaics [118], but future work is needed to determine if those results can be replicated in Ontario, specifically, and across Canada, more generally.

6. Conclusions

The results of this study make it clear that four agrivoltaic policy areas need further attention: (1) research and development, (2) education/public awareness, (3) mechanisms to support Ontario's and Canada's farmers in converting to agrivoltaics, and (4) using agrivoltaics as a potential source of trade surplus with the U.S. It is concluded that consideration should be given to the development of agrivoltaics in Ontario by first warranting agricultural research opportunities throughout the province (Section 5.1), followed by citing criteria designed specifically for these systems to allow for rapid deployment for demonstration systems for the public (Section 5.2). The results of this study suggest that policy changes (Section 5.3) are needed to increase the deployment of agrivoltaics in Ontario, including: (i) dual-use agrivoltaic systems should have a legally-recognized definition, (ii) provincial energy regimes and municipal land-use regulations should be aligned to overcome incompatibility of policies, (iii) agrivoltaics should be expressly permitted for deployment in various regions after pilot studies provide verification of technical viability, and (iv) agrivoltaics should be appropriately incentivized through policy mechanisms to encourage maximized sustainable land use. By amending land-use policies and using incentives to support agrivoltaics, the province of Ontario can ensure the preservation of farmland and growth of the agri-food sector while advancing their aggressive renewable energy, economic, and climate-related goals.

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