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Maximizing Biomass with Agrivoltaics: Potential and Policy in Saskatchewan Canada

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Abstract: Canada is a leading global agricultural exporter, and roughly half of Canada's farmland is in Saskatchewan. New agrivoltaics research shows increased biomass for a wide range of crops. This study looks at the potential increase in crop yield and livestock in Saskatchewan through agrivoltaics along with its financial implications. Then, the legislation that could influence the adoption of agrivoltaics in Saskatchewan is reviewed. Specifically, experimental results from agrivoltaic wheat production are analyzed for different adoption scenarios. The impact of converting the province's pasture grass areas to agrivoltaics and using sheep to harvest them is also examined. The results indicate that approximately 0.4 million more tons of wheat, 2.9 to 3.5 million more tons of forage and 3.9 to 4.6 million additional sheep can be grazed using agrivoltaics in Saskatchewan. Only these two agrivoltaics applications, i.e., wheat farmland and pastureland, result in potential additional billions of dollars in annual provincial agricultural revenue. The Municipalities Act and the Planning and Development Act were found to have the most impact on agrivoltaics in the province as official community plans and zoning bylaws can impede diffusion. Agrivoltaics can be integrated into legislation to avoid delays in the adoption of the technology so that the province reaps all of the benefits.

Keywords: agriculture; agrivoltaics; biomass; Canada; policy; energy; photovoltaic; renewable energy; Saskatchewan; solar energy; sustainability

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1. Introduction

Canada is one of the largest exporters of agricultural products in the world [1]. The country has more than 153 million acres of farmland, of which more than 93 million acres of land are dedicated to crops [2]. Saskatchewan consists of nearly half of the cultivated farmland of Canada and is well known for producing high-quality agricultural products. As the region has one of the most fertile lands in the world, Saskatchewan is a key contributor to meeting the ever-increasing demands of food with the growing world population [3]. For instance, the pulse sector of the province is the largest in the world and the world's largest exporter of peas, lentils, durum wheat, canola, flaxseed, and oats [3]. The following data summarized in Table 1 gives a snapshot of the share of Saskatchewan's farm products in the world's agricultural trade. Moreover, Saskatchewan also contributes a substantial amount to Canadian agri-food products as shown in Table 2. Altogether, Saskatchewan exports approximately $4.3 billion of agri-food products to the United States and $3.6 billion to China [4]. Saskatchewan is recognized worldwide for the quality of its crops, and the province is also the second largest cattle-producing province of Canada.

Table 1. Percentage of Saskatchewan's agricultural products in total world exports [3].

Crop	Share of Total World Exports
Canary Seed	56%
Peas	36%
Durum Wheat	35%
Canola Meal	27%
Oats	23%
Canola Seed	19%
Mustard Seed	19%

Table 2. Saskatchewan's contribution to Canadian agri-food market in 2021 [3].

Crop	Market Share in Canada
Lentils	89%
Chickpeas	81%
Durum Wheat	81%
Mustard	76%
Dry Peas	49%
Canola	48%
Oats	43%

These values can be increased. A new concept of combining agricultural production with solar photovoltaic (PV) electricity generation [5–9] has one extremely interesting property: agrivoltaics enables farmers to grow more biomass on a given plot of land, which increases land use efficiency [10]. Mow et al. showed that land productivity with agrivoltaics could increase by 35–73% globally [11]. The agrivoltaics-based crop yield studies that showed an increase include: basil [12], broccoli [13], celery [14], chiltepin peppers [15], corn [16]/maize [17–20], lettuce [8,21], potatoes [22], salad [22], spinach [12,22] and tomatoes [15]. These yield increases come from several mechanisms. The installation of PV modules on farmland creates a microclimate, which results in modified air temperature, relative humidity, wind speed and direction, and soil moisture [23]. These conditions are often favorable for crops as PV modules act as a shelter safeguarding plants from excessive sunlight and wind [24]. Agrivoltaics can save plants from hail too, as PVs act as a physical shield, while the crops symbiotically reduce the operating temperature of the PVs, which increases their performance [6,15,25]. Agrivoltaic installations also reduces soil erosion [26] and can even improve plant growth in deserts [27] and barren lands [26]. Crop revenue for a given area of land is thus enhanced by agrivoltaics on both the food and electrical sides [28].

Agrivoltaics includes many other benefits including: (1) renewable energy generation from PVs that offsets fossil fuel combustion, thus alleviating greenhouse gas emissions [29] and reducing global climate destabilization [30]; (2) improving water conservation [31–34] and being used to power both drip irrigation [35] and vertical growing [36]; (3) reducing agricultural displacement in favor of energy, if designed correctly [9,11,37], thus sustaining agricultural employment; (4) reducing the distance food travels, thus improving people's wellbeing (fresh food) and the environment (less emissions from transportation) [38–41]; (5) reducing adverse health effects [41] and saving lives [42] because of the reduction in pollution from the combustion of fossil fuels. Europe [43], Asia [44], and the U.S. [45] are working aggressively towards the adoption of agrivoltaics technology, and thus will have a competitive advantage over countries that do not use it. Canada currently ranks fifth in the leading agricultural exporters of the world [1], and therefore has substantial economic incentive to remain competitive in the agricultural market.

This study investigates the potential increase in crop yield and livestock in Saskatchewan due to the adoption of agrivoltaics. Experimental results from agrivoltaic wheat production [10] (for different adoption scenarios), as well as the impacts of converting the province's pasture grass areas to agrivoltaics with increased yield [23], are analyzed for the province. The economic value of these additional agrivoltaic crops, along with feeding sheep on the pasture, is quantified. Then, the legislation that could influence the adoption of agrivoltaics in Saskatchewan is reviewed. Agrivoltaics in Saskatchewan falls under various policies and regulations including lease and management policies for Agricultural Crown Land, Provincial Lands (Agriculture) Regulations, the Pastures Act, the Crown Resource Land Regulations, the Saskatchewan Farm Security Act, the Municipalities Act, as well as the Planning and Development Act. The results are discussed, and policies are prioritized to realize the complete potential of agrivoltaics in the province.

2. The Power Sector in Saskatchewan

Saskatchewan currently has a total net electric generation capacity of 5436 MW [46], which produced 24.1 TWh of electricity in 2019 [47]. This makes up around 4% of the total electricity output of Canada. SaskPower is responsible for electricity generation in Saskatchewan, although about 0.47% comes from private companies or independent power producers that sell electricity to SaskPower through power purchase agreements (PPAs) [46]. The majority of this electricity is generated through the combustion of fossil fuels, which accounts for approximately 65% of the total generation mix [47]. The largest share of electricity production is of gas-based power (39.7%), which is followed by coal that supplies 25.5% of the total generation. The remaining 35% is generated from renewable sources, mostly hydropower with a capacity of 864 MW [46]. There is ample opportunity to replace coal and gas use in Saskatchewan with solar production, as the southern part of the province receives one of the highest solar fluxes in Canada (Regina 7.15 kWh/m^2 and Saskatoon 7.10 kWh/m^2) [47].

2.1. Renewable Energy Sector

Canada has pledged to contribute to solutions addressing climate destabilization and intends to increase its non-fossil-fuel-based power generation share to 90% by 2030 [48]. Adopting agrivoltaics technology shows great promise for addressing the problem of land utilization for energy as well as minimizing climate change by decreasing greenhouse gas emissions. Previous research works have reviewed the legislations of Ontario [5] and Alberta [49]; however, no such study has been carried out for Saskatchewan, the province with the largest share of agricultural land in the country [50]. The following sections will rectify this omission.

The Government of Saskatchewan pledged to increase the renewable electricity share of the province to 50% by 2030 [51]. This would result in a reduction in greenhouse gas emissions to 40% below the 2005 level by 2030 [51]. The Pan-Canadian Framework [52] has a similar strategy, which aims to expedite the phasing out of polluting, coal-fired power plants by 2030 [51]. This further increases the need for sustainable power generation facilities to be set up in the province. To offset coal and gas with renewable energy generation, SaskPower decided to involve private companies that would sell electricity to SaskPower and in turn, SaskPower would provide electricity to its ~500,000 consumers. Overall, by 2030, SaskPower intends to increase its generation capacity to 7000 MW, of which 50% will be from renewable sources [51].

Regulatory Process for Renewable Energy Projects in Saskatchewan

All renewable energy projects are managed and approved by the Saskatchewan Ministry of Environment [51]. The procedure to ascertain the environmental impact of the project is addressed through the Environmental Assessment Act [53]. This process requires review by technical experts as well as the regional public, which provides them with an opportunity to gauge the merits of the project.

2.2. Small Power Producers Program

The Small Power Producers Program was established by SaskPower for commercial entities as well as individual customers having a maximum generation capacity of

100 kW [51]. The power generated could either be compensated for the energy imported from SaskPower grid or completely sold to SaskPower. Only one of the options is chosen by the participants, which then cannot be changed once the PPA is signed with SaskPower.

2.3. Net Metering Program

SaskPower also offers a net metering program to its customers up to a generation capacity of 100 kW (dc) [54,55]. Excess electricity generated by any customer is credited in the form of banked energy credits and received by SaskPower system at the existing rates. These banked credits are stored in the customer's SaskPower account and can then be used for the electrical energy consumed by the customer at another time. The banked energy credits are utilized/accounted for in each monthly billing cycle. A similar process can be used to regulate small-scale agrivoltaics facilities on farms in Saskatchewan. For example, any energy-intensive on-farm food processing could benefit from net-metered, small-scale agrivoltaics PV systems. Agrivoltaics examples might include market gardens [56,57] or PV-integrated roof greenhouses [58]. In addition, this approach is compatible with bringing mobile loads to the farms. For example, it has been proposed to use agrivoltaics to power computing facilities (e.g., servers, cryptocurrency [59], etc.). In turn, such computing facilities provide waste heat that can be used profitably in greenhouses [60]. For agrivoltaics to reach its full potential in Saskatchewan, larger systems are necessary.

2.4. Saskatchewan's Public Perception on Clean Energy Technology

Although existing solar PV-based power generation accounts for less than 1% of the total electricity generation in Canada [61], there is a massive desire to adapt renewable energy to compensate for traditional (fossil-fuel-based) power generation sources or even for services such as heating and transportation. In 2015, an opinion survey conducted by Oraclepoll Research on behalf of CanWEA to gain insight into the public's view regarding renewables found [51]:

- More than half of the people preferred renewable means of electricity generation;
- More than three-quarters thought alleviating emissions was important;
- Three-quarters believed that the government of Saskatchewan needs to put in more effort to develop the renewable energy sector.

Another survey was conducted in 2016 by Vote Compass, which found that almost 68% of Saskatchewan's population suggested investing more in the renewable energy sector [51]. These surveys are a good indicator of the public pulse and suggest acceptance among the general public regarding renewables. Studies in the U.S. showed that agrivoltaics was viewed favorably by the solar industry [62], farmers [63] and substantially increased the public acceptance of large-scale PV systems [64]. Public demonstrations of experimentation can build further confidence in adopting the technology [65].

3. Saskatchewan and Sustainability

3.1. Saskatchewan's 30 by 30 Goals

The government of Saskatchewan has set up an ambitious target for the province outlined in its 30 goals to be achieved by 2030 [66]. One of these targets includes 100,000 new employment opportunities in the region [66]. The solar industry generates 2.1 employment opportunities per MW for utility-scale projects, while the number significantly increases to 26.6 for small-scale residential projects [67]. Moreover, the total job-years per GWh associated with the solar industry is 0.87, which is nearly 8× that for coal (0.11 job-years per GWh [68]). Therefore, one of the benefits of agrivoltaics is that it provides avenues for new job opportunities, which are higher than the conventional fossil-fuel-based power generation resources. Simultaneously, agrivoltaics maintains agricultural employment, and the increased yield may provide even more agricultural job opportunities.

Another objective is to increase the existing provincial export share by 50% [66]. Agrivoltaics has been shown to increase biomass yield and hence can play its part to achieve this target based on physical products alone. As the PV generation potential from a reasonable amount of agrivoltaics deployment in the province far outstrips the current demand, there is also the potential for exporting electricity to the unclean/polluting grids in the U.S. [69].

Moreover, agrivoltaics can also assist in meeting one of the 30 aims to increase the value of agri-food exports to $20 billion [66]. Increasing the crop yield to 45,000,000 metric tons and agricultural-related revenue to $10 billion are other ambitions of the government of Saskatchewan [66] that align well with agrivoltaics technology.

In addition, as agrivoltaics integrates PVs with agriculture, it becomes a source of technological growth. Companies are now experimenting with different PV designs (translucent or semitransparent, colored PV modules [70–75], and color-shifting agrivoltaic-specific PVs [76–82]) and configurations to reap more benefits from the technology. Therefore, agrivoltaics can contribute substantially to promoting technology in Saskatchewan, which is also one of the objectives to be met by 2030 [66]. Finally, as agrivoltaics involves solar PVs, which are a clean and sustainable electricity generation source, it fits perfectly with Saskatchewan's climate targets and satisfies another one of the 30 goals [66].

3.2. Greenhouse Gas Emissions

In 2020, the total greenhouse gas emissions in Saskatchewan were 65.9 MT of carbon dioxide equivalent [83]. This value is an increase of almost 46% compared to 1990 levels, but a reduction of 8% from 2005 levels [83]. The per capita emissions in Saskatchewan (55.9 tons per capita) are the highest in Canada, which has average emissions of 17.7 tons per capita [83]. One of the leading contributors to these greenhouse gas emissions is the power generation sector, which makes up almost 19% of the total emissions [83]. This is understandable due to the province's heavy reliance on fossil-fuel-based electricity generation. Interestingly, the emissions contribution of the agricultural sector is even higher and amounts to a quarter of the total emissions for the province.

Agrivoltaics could be a major contributor to reducing greenhouse gas emissions from both electricity as well as the agricultural sector. The reduction in emissions from the power sector is obvious as PVs are a renewable and sustainable source of electricity generation. For the agricultural sector, Scope 1, 2 and 3 emissions can also be alleviated if PVs are coupled with agriculture. Through agrivoltaics, electricity and fertilizers can be produced on farms [84–87]. Therefore, there is no need to transport these products over long distances for farming operations, thereby reducing Scope 1 emissions. Agricultural operations require extensive use of vehicles. Individuals can use electric vehicles for the same purposes, and they can be charged using electricity generated through agrivoltaic installations, thus reducing Scope 2 emissions. The power generated can also be utilized for other farming needs to reduce Scope 2 emissions. Lastly, Scope 3 emissions reduction is possible if the electric vehicles are used as a means of transportation for carrying the crops. The electric vehicles can then be recharged using PV-farm-generated electricity. Additionally, the on-farm production of fertilizers can significantly reduce the transport mileage, which again contributes to minimizing GHGs. Since solar is a sustainable form of energy [88], it would indeed be beneficial for the regional as well as global environment if more PV-based power plants were installed in the country. Studies have indicated great promise for agrivoltaics in Canada, i.e., the deployment of PVs on farmland [5,89]. Energy produced by solar PV panels over their warranted lifetime (between 25 and 30 years) is several times the amount of energy that is utilized to produce it; hence, PV technology is a net energy producer [88]. Studies have shown that the technical lifetime of PVs is even higher [90–92]. As PV technology grows to become ever more efficient [93], the payback times have been reduced to less than one year [94].

3.3. Saskatchewan and Agrivoltaics

Saskatchewan consists of the largest area of farmland in Canada, i.e., approximately 40%. With the population density (Figure 1) overlapping with one of the most favorable solar flux potentials in the region in terms of crop land (Figure 2), it is a suitable territory for agrivoltaic installations. To offset the entire province's fossil-fuel-based electricity generation share, only 0.17% of farmland is required if single-axis-tracking-based agrivoltaic systems are used, and 0.26% of agricultural land is needed for a vertical configuration [89]. The total potential of agrivoltaics in Saskatchewan for 1% of the agricultural land is 76,087 GWh/year for vertical PV systems and 116,675 GWh/year for single-axis tracking PV systems [89].

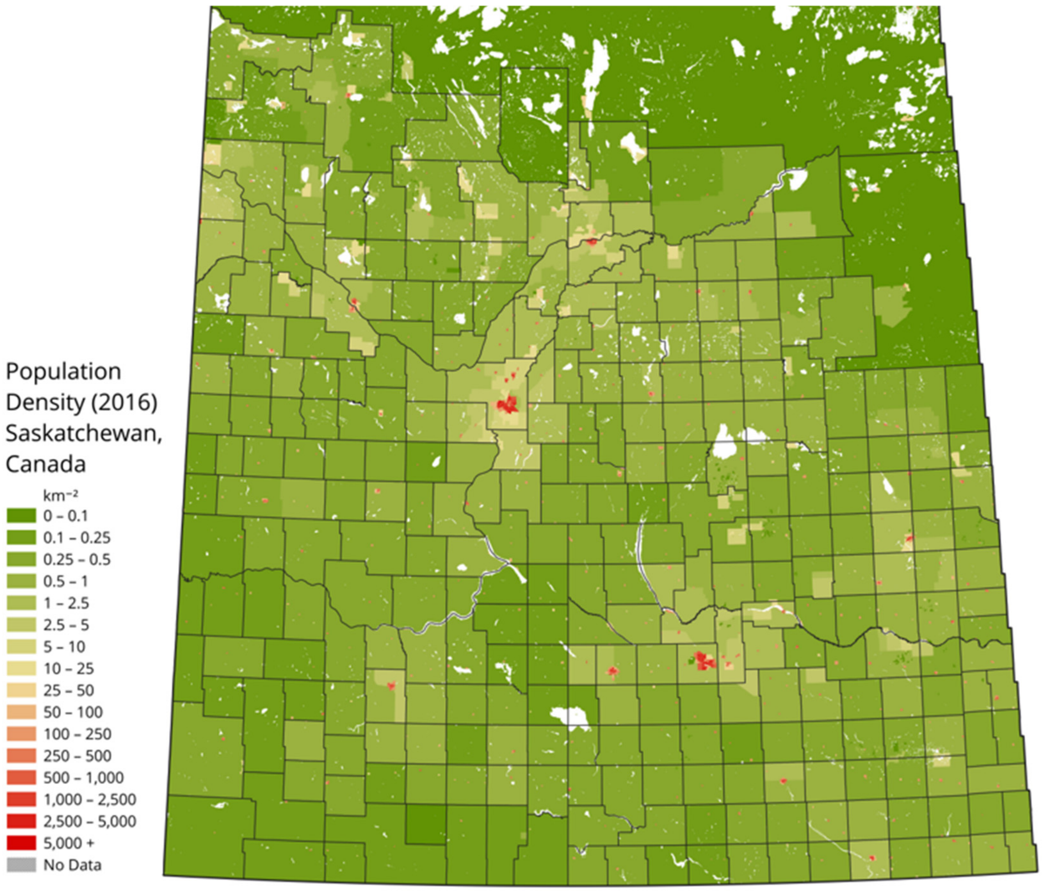


Figure 1. Population density of southern Saskatchewan, Canada [95].

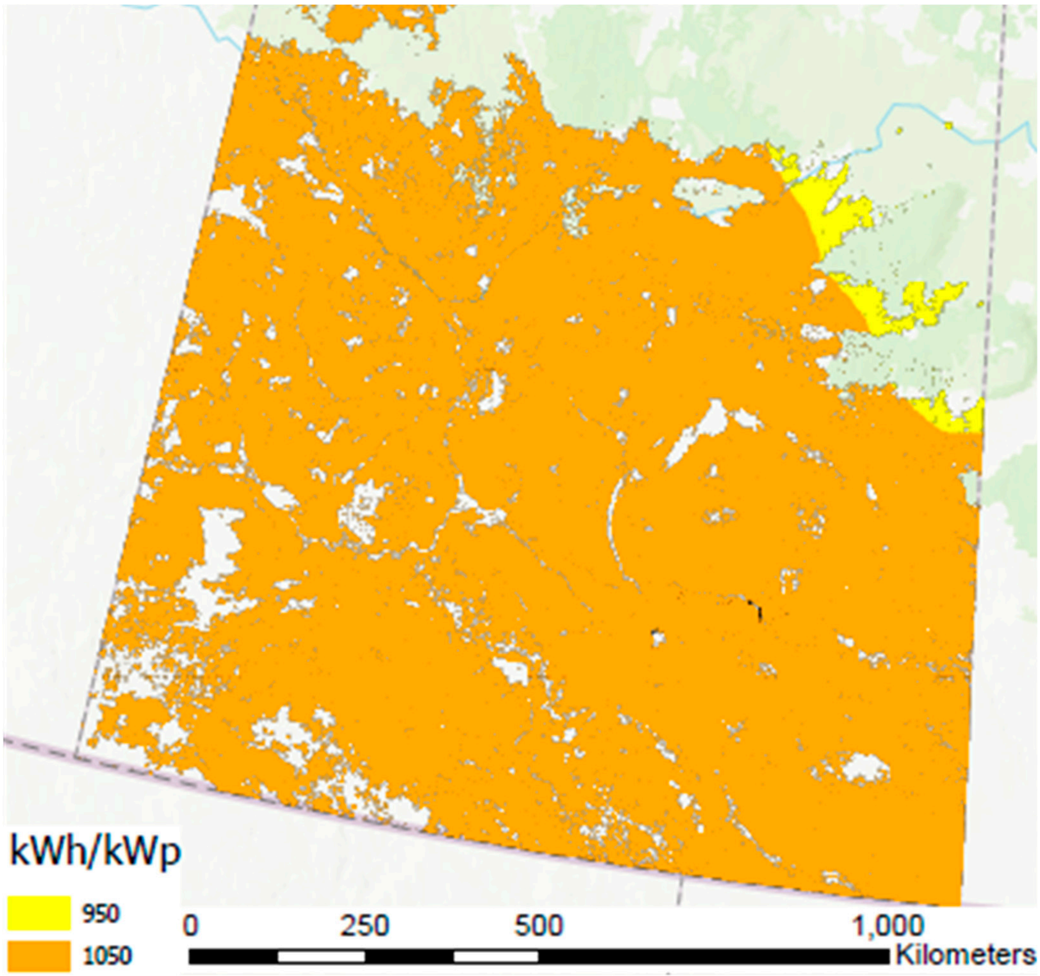


Figure 2. Conventional photovoltaic potential (in kWh/kWp) of south-facing, vertically oriented arrays in the farmland regions across Saskatchewan (adapted from [89]).

4. Methods

From the peer-reviewed literature related to the increase in crop yield with agrivoltaics, wheat and pasture were selected as the crops for analysis in Saskatchewan. A study in Germany near Lake Constance with coordinates of 47.6363° N, 9.3892° E indicated increases of 3% in wheat production under agrivoltaics [10], and another study on agrivoltaics for wheat showed a 2% increase in yield at three locations (Channay with coordinates of 47.8816° N, 4.3311° E, Rivals with coordinates 43.0725° N, 2.3814° E and Valpuiseaux with coordinates 48.3963° N, 2.3056° E) in France [96]. As these values are similar, the further northern example of Germany was used in order to more closely align with the growing environment in Canada. The average PV potential of Lake Constance is approximately 1172.9 kWh/kWP [97], while Saskatchewan's average PV potential is 1358.6 kWh/kWp [98]. Increases in production were also observed in Oregon (latitude 43.8041° N, longitude 120.5542° W), U.S., for pastures [23]. The PV potential of the location is 1582.1 kWh/kWp [99]. The calculations were carried out using the current prices of wheat and forage in Saskatchewan.

For the potential additional yield of crops produced, first the total amount of crops cultivated in Saskatchewan was determined. The baseline crop, B_c, is the quantity of wheat in tons produced in the province. The amount of wheat produced in Saskatchewan was ascertained from government of Saskatchewan values [100]. Next, the potential increase in crops was estimated using:

$$A_{wheat} = B_c \times P_{wheat} \quad [\text{tons}] \tag{1}$$

where P_{wheat} is the percentage increase in crops due to agrivoltaics application based on the literature, given as 3% for wheat [10].

To remain conservative in the estimations, for pastures, the baseline value ($A_{conventional}$) was determined using the lowest yield of forage per acre l_f [101] and multiplying it by the total pastureland (l) in the province [102]. The total amount of forage due to agrivoltaics application, $T_{pasture}$, is given by:

$$T_{pasture} = P_{pasture} \times y_f \quad [\text{tons}] \tag{2}$$

where $P_{pasture}$ is the ratio of the forage yield for shaded and unshaded regions of pastures compared to the control configuration—1.9 for shaded regions (90% increase) and 0.84 for unshaded regions (16% decrease) [23]—and y_f is the forage yield for shaded and unshaded regions based on the conventional value of 0.6 ton/acre (lowest). See details of agrivoltaic row spacing to determine shaded areas in Figure 3.

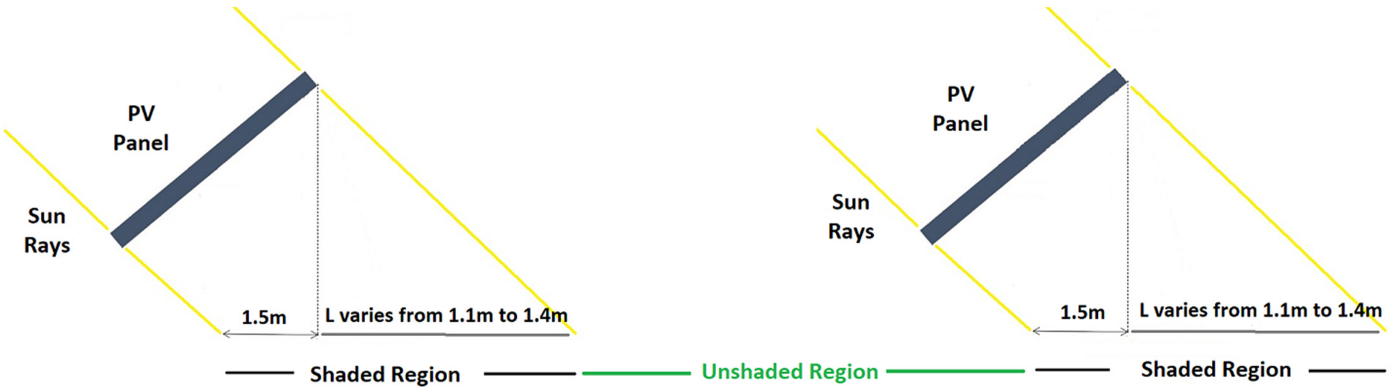


Figure 3. Side view of conventional solar PV farm used by Adeh, shaded and unshaded regions for pastureland are detailed (note that the angle of the sun in the sky prevents shading the front half of the array underneath the module).

To determine the additional yield of forage from pastures, the total pastureland in Saskatchewan was divided into shaded and unshaded regions based on the proposed PV installations. This was done because the study [23] in Oregon, U.S. indicated a slight decrease (16% less) in pasture that was grown in the unshaded regions (i.e., between the PV rows) when compared to the conventional/control configuration pasture, while a 90% increase in yield was noted for grassland grown in the shaded region. Using the same PV configuration as Adeh, a sensitivity analysis was carried out for the shaded region in the range of 2.6 m to 2.9 m, while the unshaded region ranged from 3.4 m to 3.1 m, for a 6 m section of land. Consider the first scenario in which the shaded region was 2.6 m and the unshaded was 3.4 m (of the total 6 m length considered). This means that 43.33% of the pastureland was shaded and 56.67% was unshaded. Multiplying these percentages by the total pastureland yielded the total area of pastureland, which was either shaded or unshaded. In the second scenario, 2.9 m was considered shaded while 3.1 m weas considered unshaded. Using these values of shaded and unshaded areas of pastureland, the total shaded and unshaded area of pastureland was determined. Using the yield of forage per acre (baseline yield considered was the lowest yield, i.e., 0.6 tons/acre), the total yield for each area of pastureland was estimated based on the control configuration (the lowest yield of 0.6 tons per acre). Next, the impact of agrivoltaics was applied by multiplying these yields (y_f) by 0.84 for the unshaded region and 1.9 for the shaded region using equation (2) to ascertain the total yield for pastureland in Saskatchewan. This means that two values of total yields were finally estimated using the baseline yield (0.6 tons/acre) for the two sensitivities of the shaded (2.6 m and 2.9 m) and unshaded regions (3.1 and 3.4 m). The difference between the total yield for pastures due to agrivoltaics, $T_{pasture}$, and the total yield without agrivoltaics ($A_{conventional} = l_f \times$ total Saskatchewan pastureland) is the additional yield for pastures due to agrivoltaics, $A_{pasture}$.

$$A_{pasture} = T_{pasture} - A_{conventional} \quad \text{[tons]} \tag{3}$$

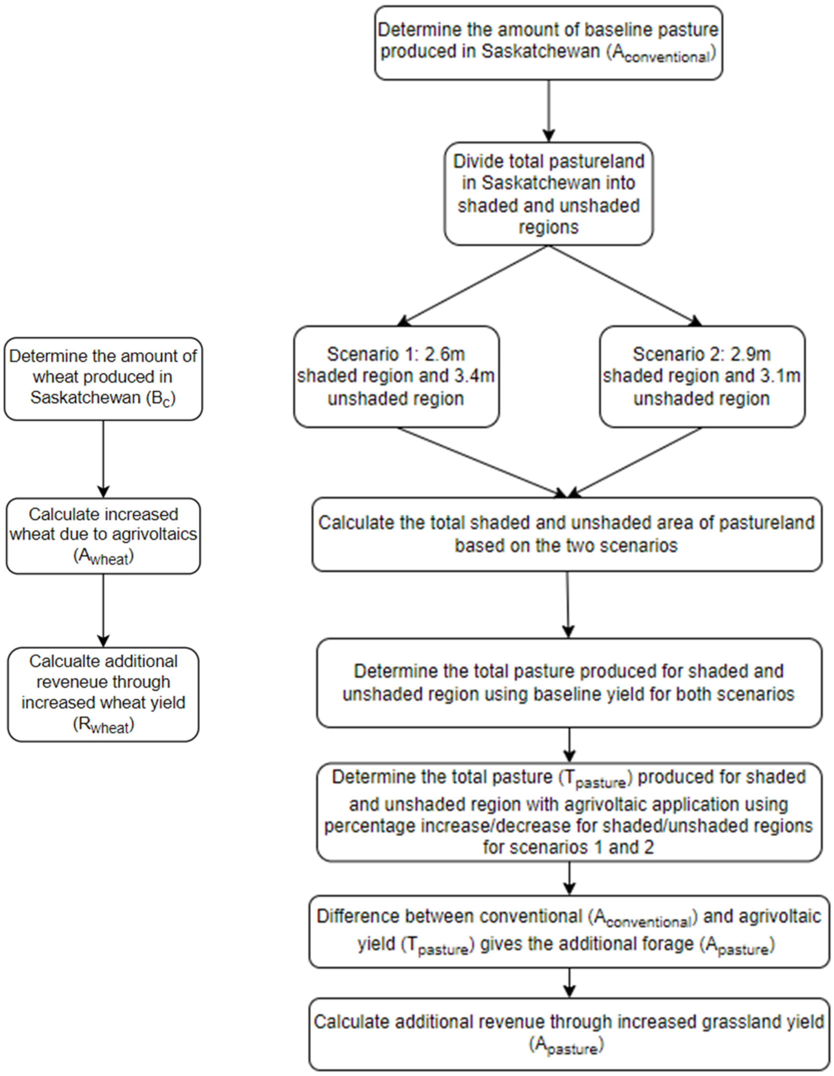
Additional revenue, R, from increased amount of wheat or pasture is given by:

$$R_{wheat/pasture} = A_{wheat/pasture} \times M_{wheat/pasture} \quad \text{[CAD (\$)]} \tag{4}$$

where $M_{wheat/pasture}$ is the market value of produce in CAD ($) [101,103]. Moreover, additional revenue, R_e, due to the installation of PV panels and subsequent electricity generation is given by:

$$R_e = P_e \times E \quad \text{[CAD (\$)]} \tag{5}$$

where P_e is the electrical power potential of farmland on which wheat/forage is grown and E is the electricity rate in Saskatchewan (CAD$0.14228/kWh) [104]. The following flow chart shown in Figure 4 summarizes the methodology used for the calculations involving (a) wheat and (b) grassland.



(**a**) (**b**)

Figure 4. Calculation flow chart for (**a**) wheat and (**b**) grassland.

Electric power potential was determined using the open-source System Advisor Model (SAM) [105]. Energy modeling in SAM was carried out by selecting Heliene 144HC-460 bifacial PV modules [106]. The PV potential was calculated using different agrivoltaic configurations appropriate for the specific crops (vertical and single-axis tracking for wheat and a fixed racking system for pastureland). First, the total land cover for wheat cultivation and pastureland was ascertained and considered to be a square. Next, the length of one side of the square was determined by taking the square root of the total area. For the analysis, two different agrivoltaic system configurations were considered, which could accommodate wheat production with minimal impact on farming practices: (1) vertical south-facing PVs with a tilt of 90° and (2) single-axis tracking system with a tilt of 0° (tilt of 0° being the default setting for single-axis tracking application in SAM). For pastureland, fixed-tilt (latitude) south-facing PV systems were built from mini-arrays, each with a capacity of 1200 W [107]. The modules (three in total—each panel approx. 2 m in length vertically and approx. 1 m horizontally) were oriented horizontally instead of vertically to have the same inclination length (approx. 3 m), as discussed in the work by Adeh et al. [23].

For wheat farmland (e.g. Figure 5), a vertical 2700 W PV mini-array with a width of 4.8 m [108] was used for vertical PV simulations, while a 15,000 W single-axis tracking system with a width of 23 m and depth of 4 m [109] was used as the second system type for PV simulations. To calculate the number of arrays in a single row, the length of one side of the land was divided by the width of the array. Next, the inter-row spacing of 20 m was used to estimate the number of rows for single-axis tracking and vertical PV systems that were installed in the wheat farm area. This inter-row spacing was considered to ensure the ease of movement of farm/agricultural equipment and machinery. With sufficient spacing between the rows of PV panels, the machinery required for cultivation of wheat can be operated without any hinderance. The figure below depicts the configuration of PV panels on a wheat farmland:

Figure 5. Agrivoltaic system pictorial design for wheat-growing agricultural land with sufficient spacing between solar PV rows ensuring ease of operation of agricultural machinery.

For pastureland, a typical PV system configuration was considered based on [23] with an inter-row spacing of 3 m. Using the quantity of vertical, single-axis tracking and fixed array in one row and the total number of rows in the given piece of land, the total installed PV system capacity was determined.

Additional yields of forage also result in the ability to graze more livestock. Hence, agrivoltaics leads to a greater number of cows [110], lambs [111], sheep [112,113], and rabbits [114] that can be raised from the enhanced yield for pastureland. For the analysis, 80 lb.

lambs/sheep were selected from the available livestock grazed in Saskatchewan because of the well-established sheep agrivoltaics and their superior environmental impact [113]. Considering the amount of forage consumed by sheep in a single year, the additional number of sheep, A_s, from increased forage was estimated using the following equation:

$$A_s = L_a/F_s \qquad \text{[sheep]} \qquad (6)$$

where F_s is the amount of forage consumed by a sheep/year (i.e., 0.75 tons) [115] and L_a is the additional yield of forage from agrivoltaics in tons. Additional revenue from raising the sheep, R_{sheep}, was determined next by multiplying the price of sheep, P_{sheep}, (using price of \$2.3/lb for an 80 lb lamb [116]) by A_s determined from Equation (6):

$$R_{sheep} = A_s \times P_{sheep} \qquad (\$) \qquad (7)$$

5. Results

If the available pastureland and the area over which wheat is grown in Saskatchewan is transformed to agrivoltaics, then significant amounts of wheat and forage as well as additional revenue will be generated, as shown in Table 3 Using Equation (1), the additional crop yield was determined. Inputs for the percentage increase in wheat and forage were considered from the available literature. Next, Equation (2) was used to determine the revenue from the increased crop yields by using the values of additional produce from agrivoltaics application and the market value of produce.

Table 3. Estimated increase in yields and revenue of forage and wheat due to agrivoltaics application.

Crop	Normal Production (Tons)	Price ($/Ton)	Additional Crop Yield Due to Agrivoltaics (Tons)	Additional Crop Yield Value (CAD$)
Wheat (low value)	14,766,371	376.62 [103]	442,991	166,839,319
Wheat (high value)		496.69 [103]		220,029,264
Forage (low value)	9,960,000	91.88 [101]	2,981,360	273,927,356
Forage (high value)		277.48 [101]	3,509,240	973,743,915

From Table 1, it is evident that the increase in forage for pastureland was quite significant based on the 90% increase in biomass observed in Oregon, using fixed-tilt conventional PV systems [23]. The estimates, however, should be carefully examined as similar increases in productivity may not be observed in Saskatchewan. The calculations, however, give fair insight into the potential of increased revenue that can be achieved from agrivoltaics applications. The estimates for forage value were also determined using conservative numbers of forage production (0.6 tons per acre). The results indicate that an additional CAD$273 million worth of forage can be produced on 16.6 million acres of pastureland in Saskatchewan if it is converted to agrivoltaics. These numbers are driven by the lowest price range of forage at CAD$91.88/tons. The revenues increase considerably if the more favorable value of CAD$ 277.48/ton of forage is considered. The additional profits amount to more than 973 million dollars in such a case.

Calculations following Equations (1) and (4) were also performed for wheat, which showed increased revenues of CAD$166 million and CAD$220 million considering low and high values of wheat, respectively.

Due to the additional forage produced with agrivoltaics applications, more cattle can be grazed and raised. Table 4 summarizes the additional number of 80 lb. sheep/lambs that can be raised on pastureland assuming 0.75 tons of forage is consumed by a single sheep in one year, if agrivoltaics technology is adopted in Saskatchewan. The economic value of the sheep is based on the average price for an 80 lb. sheep/lamb of $184 [116].

Table 4. Additional grazing of sheep and subsequent revenue achieved from it.

Additional Forage from Agrivoltaics (Low and High)	Additional Sheep/Lambs Grazed	Additional Revenue from Sheep/Lambs (Million $)
2,981,360	3,975,146	731.4
3,509,240	4,678,986	860.9

The potential revenue generated from the increased number of sheep is substantial. The results indicate that approximately $860 million of sheep/lambs could be grazed using the additional forage produced from agrivoltaics.

Finally, the additional revenue from electricity generation by incorporating agrivoltaics was determined using two different configurations of PV systems for wheat and a fixed-tilt configuration for pastureland. Understandably, considerable variation was found between the two designs for vertical and single-axis-tracking-based agrivoltaic systems, as seen in Table 5.

Table 5. Revenue from electricity generated from agrivoltaic installations on pastureland and farmland on which wheat is harvested using vertical and single-axis tracking configuration.

Crop & Type of PV Configuration	Area Harvested (Acres)	Annual Energy from Agrivoltaic Installations (GWh)	Revenue from Electricity (Billion CAD$)
Wheat (Vertical—south-facing)	13,250,000	1,740,280	247.6
Wheat (Single-Axis Tracking)	13,250,000	2,580,542	367.1
Forage (Fixed latitude tilt)	16,600,000	9,209,876	1310.3

As can be seen from Table 5, there exists huge potential of PV installations on agricultural farmland for wheat as well as pastureland in Saskatchewan. Vertical racking PV systems facing south installed on wheat farmland would result in the electrical output of 1740 TWh annually with an annual revenue of approximately $247 billion. For the stabilization of the grid, the panels may be oriented east/west so that more energy is generated during morning and evening. The simulations indicate that 1676 TWh of energy can be produced from vertical east/west-facing PVs. The values increase significantly for single-axis tracking systems, which are more efficient, generating $367 billion of annual economic output. Approximately 16.6 million acres of land in Saskatchewan is dedicated to pastureland. The installation of agrivoltaic systems results in annual electricity output worth $1310 billion. To put these numbers into context, the total electricity consumption in Canada in 2019 was 632.2 TWh [47]. Thus, the lowest electrical output of the four cases considered, even with a suboptimal orientation (1676 TWh) has almost thrice as much energy potential than the total electricity consumption of Canada. In the United States, the total electricity consumption for the year 2021 was 3900 TWh [117]. Combining the electrical output of converting the wheat-cultivating farmland and pastureland of Canada to agrivoltaics can even meet all of the United States' current electricity requirements.

It is possible that by maximizing the biomass production in Saskatchewan, Canada could begin massive electricity exports to the U.S., but another option would be to use the electricity domestically, as decarbonization encourages electrification. There are three main areas of potential electrification: (1) industrial, (2) transportation, and (3) residential. In 2021, the energy requirement for the industrial sector in Canada was 2,887,141 terajoules or 801 TWh [118]. Similarly, the transportation sector in Canada consumed 2,333,486 terajoules or 648 TWh of energy. Moreover, the residential sector was supplied with 1,320,400 terajoules or 366 TWh of energy. Altogether, this amounts to 1815 TWh of energy. This is approximately only 70% of the total energy delivered by single-axis tracking agrivoltaics on farmland dedicated to wheat. Moreover, approximately 95% of the energy required by industrial, transportation and residential systems in Canada can be provided by vertical agrivoltaics on farmland dedicated to wheat.

Figures 6–8 summarize the scale of the additional revenue for crops, sheep, and solar electricity, respectively, for the various agrivoltaics scenarios in Saskatchewan. As can be seen from Figure 6, the additional revenue from high-value forage is greater than four times the additional value from high-value wheat. Compared with low-value wheat, the economic advantage of increased pasture production with agrivoltaics is almost six-fold. Similarly, the financial benefits from grazing sheep on additional forage increases by one-fifth considering the high value of forage/acre (2.2 tons/acre) when compared with the lower value (0.6 tons/acre) (Figure 7). Employing single-axis tracking system on agricultural land used for wheat farming increases the electrical output by half of what is generated through vertical designs (see Figure 8). Moreover, the electrical potential of transforming pastureland to agrivoltaics in Saskatchewan is almost five times more than the potential of vertical designs and 3.5 times more than the potential of single-axis tracking designs used on wheat farmland.

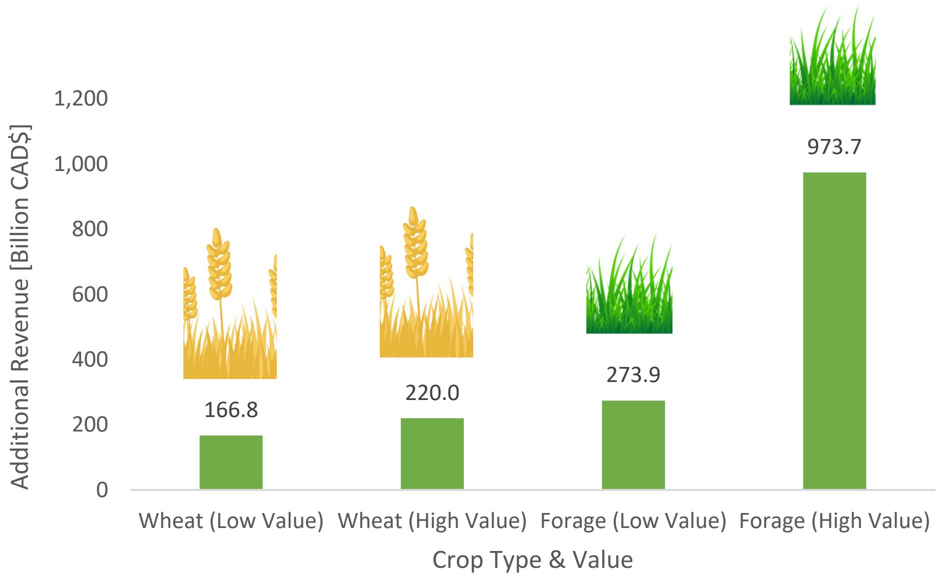


Figure 6. Additional revenue (low and high) from additional wheat or forage that can be produced from agrivoltaics in Saskatchewan.

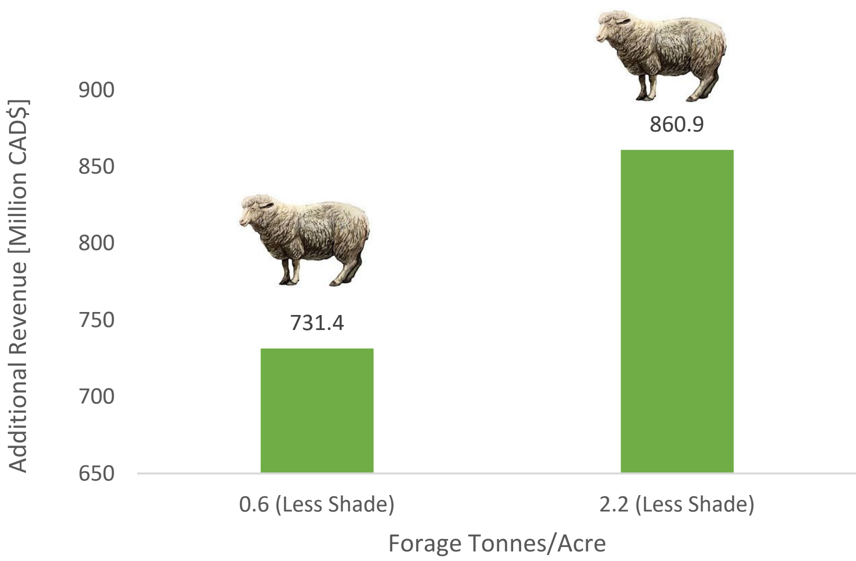


Figure 7. Additional revenue from sheep that can be grazed on land due to additional forage as agrivoltaic grass increases. Plots are developed for the two scenarios of different shaded and unshaded regions.

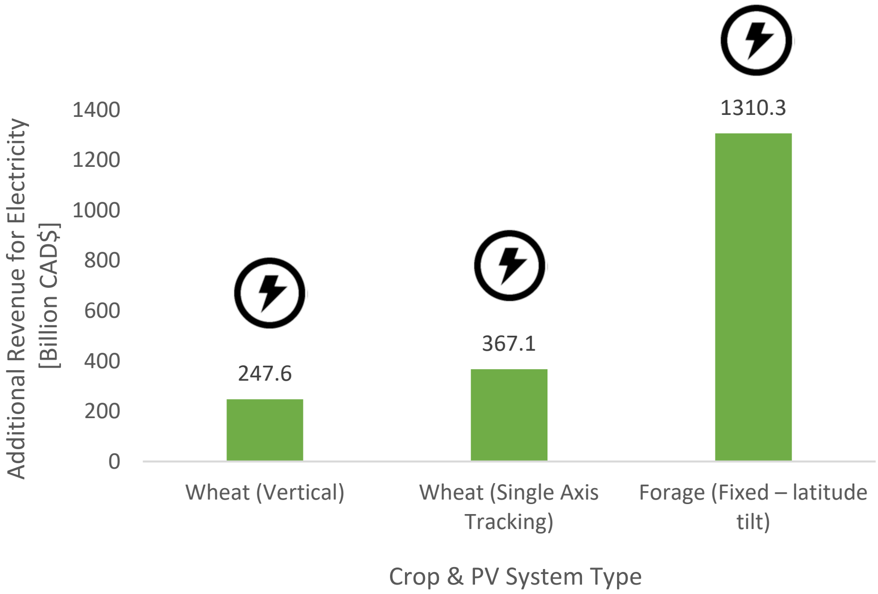


Figure 8. Additional revenue from electricity generated from agrivoltaic farms on farmland dedicated to wheat (vertical and single-axis tracking designs) and pastureland (fixed-tilt traditional PV system).

6. Legislation Review for Agrivoltaics

It is clear that the results indicate that the energy potential of agrivoltaics in pastureland and wheat crop land in Saskatchewan is enough to have a massive impact on the electricity sector and carbon emissions for North America as a whole. Similarly, the calculations of the economic impact of agrivoltaics transformation would be substantial. Clean electricity generation worth billions of dollars could be produced without any adverse impact on crops and in fact, would be expected to massively increase biomass, also worth billions. To enable this to happen, there are both technical and legislative hurdles to overcome. Agrivoltaics has already been proven at the MW scale, but developing it at the GW scale in Saskatchewan is left for future work. Here, the first step of developing the policy enabling the systems to be installed is targeted by reviewing the legislation in Saskatchewan relevant to agrivoltaics. Table 6 summarizes the laws and policies that can influence agrivoltaics in the province:

Table 6. Laws, regulations and policies that impact agrivoltaics in Saskatchewan.

Legislation	Description	Relevance to Agrivoltaics
Lease Policy for Agricultural Crown Land	The Lease Policy for Agricultural Crown Land document specifies the requirements for leasing agricultural crown land while ensuring its sustainability. The leases are to be allocated to the highest bidder (Canadian citizens or permanent residents) via auction for a period of 33 years [119]. The Minister is authorized to draft a policy specifying lease holder selection criteria according to which the land is leased to the interested person. The authority of the Minister lies in Section 3-2(1) (b) of The Provincial Lands (Agriculture) Regulations. One of the eligibility requirements for leasing agricultural crown land is to meet the requirements of Saskatchewan Farm Security Act [120]. The policy does not explicitly state the usage of agricultural crown land. There is a provision in the lease policy document termed “direct lease” where the lease may be issued directly if it is a public interest. The same provision could be of interest if the use of land is intended for agrivoltaics technology, and the timeline matches reasonably well with the technical lifetime of PV systems that are normally under warrantee for 25 years [119].	Installation of solar panels on agricultural crown land may require lease acquisition.

Table 6. *Cont.*

Legislation	Description	Relevance to Agrivoltaics
Management Policy for Agricultural Crown Land	The Management Policy for Agricultural Crown Land document broadly details the usage of agricultural crown land to ensure they are within the appropriate and applicable land use regulations [121]. There are two types of abuses specified in the policy: (1) resource abuse, where the lease holder violates the lease condition, which could have possible detrimental effects on the land, and (2) administrative abuse, where the lease holder violates the administrative conditions mentioned in the lease. The document subsequently specifies the process to authenticate an abuse claim and the time allowed to correct those claims based on their type/nature.	To ensure that agrivoltaics does not have any long-term detrimental effects on the land, a decommissioning and recycling plan must be included and funded with projects. PV systems are readily recyclable [122] but may need policy support to be incentivized [123], and decommissioning plans are already included in many utility-scale PV systems [124].
The Provincial Lands (Agriculture) Regulations	The Provincial Lands (Agriculture) Regulations discuss the criteria to lease provincial agricultural land, issuance of permits, licenses, easements, and utilization dispositions as well as cancellations of the same [125]. An agricultural lease is defined as a lease issued for farming, grazing, harvesting, or running a domestic game farm. The lease may be issued for the following purposes: • Farming crops; • Grazing; • Harvesting of hay; • Operation of game farm; • Oil, gas, and mineral development works. Similarly, permits may be issued for (1) cultivation, (2) livestock grazing or (3) hay harvesting purposes. Moreover, easements and utilization dispositions can be allocated for (1) exploration and development purposes in areas of minerals, oil and gas, etc., (2) understanding the feasibilities of carbon sequestration, (3) research, and most importantly for agrivoltaics, (4) for the assessment and investigation of clean energy technology. The regulations prohibit any individual from carrying out any improvements related to buildings or structures (e.g., PV racking) unless appropriate approvals have been acquired. The regulations allow the Minister to sell leased agricultural land, issue a lease, permits, licenses and easements to individuals for purposes other than those specified in the regulations if the Minister considers them in the "public interest".	Although there is no specific prohibition of agrivoltaics deployment in the regulations as reviewed in the document, this provision can certainly be applied to agrivoltaics.
The Pastures Act	The Pastures Act regulates the formulation, operation, maintenance, as well as control and supervision of pastureland in the province [126]. One of the purposes of the act is the establishment of plans and schemes that foster, stimulate or conserve the ecological, social, and commercial utilization of pastures. The Minister is considered all-powerful to carry out improvements of pastureland that the Minister deems appropriate. Moreover, the Minister may also suggest programs that serve the purpose of environmental conservation or economic development.	Although further study is needed to determine the impacts of various PV systems on pastureland in Canada, the results in Corvallis, Oregon, U.S. are promising [23] and could be used in Saskatchewan.
The Crown Resource Land Regulations	Crown resource land refers to all lands that fall under the responsibility of the Minister. The term resource land disposition is used to identify any disposition allocated in conjunction with Crown Resource Land Regulations, which allow the entry, usage, or occupation of crown resource land [127]. The regulations limit the disposition period to 33 years, while they also mention that the disposition holder must ensure minimal damage to the land itself or any improvement installed on it [127].	This provision could have a potential impact on agrivoltaic installations. Although, experiments indicating minimal or no adverse effects on soil as well as enhanced yield could help pave the way for the technology in the province [127].

Table 6. *Cont.*

Legislation	Description	Relevance to Agrivoltaics
Permitting Policy Agricultural Crown Land	The permitting policy allows vacant or unused crown land to be leveraged under short-term disposition arrangements. These include lands that are (1) advertised for lease, but could not be leased, (2) marketed for auction, but could not be sold, (3) lands for which the lease was terminated, (4) surrendered lands, or (5) issued prohibition disposition prior to the cultivation season [128]. Lands that are generally leased on a long-term basis are referred to as definable areas, whereas for other vacant lands (undefinable areas), permits are issued on a first-come-first-serve basis. In both cases (definable and undefinable areas), the permit holder must ensure compliance with the Saskatchewan Farm Security Act [120].	Installation of solar PVs on unused or vacant agricultural crown land may require permit issuance.
The Saskatchewan Farm Security Act	The Saskatchewan Farm Security Act intends to provide security to family farms and conserve farmland for farmers of the province [120]. The act defines farming as an activity of breeding and raising livestock and poultry, dairy operations such as the production of milk, etc., apiculture, soil tillage, fur farming and other related operations carried out for the purpose of producing primary agricultural products and animals.	Nothing specific is mentioned related to farm use in the act, which explicitly prohibits agrivoltaics deployment. Additionally, it is clear that agrivoltaics involves farming as defined in the act.
The Municipalities Act	The main aim of the Municipalities Act [129] is to draft a framework for how municipalities are governed while upholding the interests of its people. It equips municipalities with authority to adapt to current and future challenges for its residents using novel techniques. Agrivoltaics seemingly fits well with the goal of the legislation and provides a sustainable option. The municipalities ought to function via a council that approves bylaws in connection with construction impacting amenities of the area, approvals and prohibitions, economic ventures, and issuances of licenses, permits, etc. Moreover, these bylaws deal with requirements and criteria for the issuance of these licenses or permits or restricting any activity or business unless the required authorization is received.	Agrivoltaics seemingly fits well with the goal of the legislation related to the adoption of novel techniques and provides a sustainable option. Some of the legislation's features may act as a deterrent to agrivoltaics as the municipalities have the authority to prohibit its deployment in Saskatchewan. Although, miscellaneous powers of the municipalities allow them to grant rights with regards to land and other constructions which can benefit agrivoltaics.
The Northern Municipalities Act	The primary objective of the Northern Municipalities Act is the provision of a framework for municipalities to be administered in the best interest of, as well as to render equitable treatment to, its residents. The act empowers municipalities to govern the region and address the current as well as future requirements of its residents in the best possible way. Agrivoltaics aligns well with this purpose of the act and provides a sustainable way to meet the existing and probabilistic needs of the coming generations. It defines buildings as structures that are utilized as occupational spaces or structures that are a means to hold up or provide shelter for any sort of usage or occupation [130]. The municipalities operate and function through the formation of a council that passes bylaws to implement its powers. The bylaws can be related to buildings or activities that influence amenities of the locality, regulations, and prohibitions dealing with industries and businesses as well as provision of appropriate approvals such as leases, permits, etc. The bylaws may also be formulated to underline terms and conditions for licenses and permits, or forbid any development works until appropriate approvals are acquired. The council is also empowered to pass licenses for special businesses. The act also defines the methodology to provide a public utility service, which is executed via a controlled corporation or agreement with an individual. The rates are approved by the Saskatchewan Municipal Board. Particularly interesting for agrivoltaics is that the act also signifies the establishment of municipal development corporations with the intention of ascertaining commercial opportunities and developing comprehensive plans that benefit the regional population.	Similar to the Municipalities Act, the Northern Municipalities Act can have possible implications for agrivoltaics deployment. Although the current regulations do not include it, agrivoltaics could be made part of the list to regulate it as a novel business opportunity for northern Saskatchewan.

Table 6. *Cont.*

Legislation	Description	Relevance to Agrivoltaics
The Agricultural Operations Act	The Agricultural Operations Act [131] provides explanations of terms such as agricultural operations, livestock operations, agricultural practices, etc. For agrivoltaics, the definitions of agricultural operations and normally accepted agricultural practices may be used to support development. The following activities are referred to as agricultural operations carried out on a farm in order to make profits: • Cultivation of farmland; • Production of crops, hay, vegetables, fruits, etc.; • Breeding and nurturing livestock including horses, poultry, etc.; • Beekeeping; • Production of dairy items such as milk, eggs; • Operation of equipment relating to agriculture. Any other activity may also be categorized as an agricultural operation provided it is prescribed the same in the act. A "normally accepted agricultural practice" is one that is carried out in a manner appropriate and in accordance with established conventions. It may even involve novel technologies and practices provided suitable conditions [AOA]. According to the act, the Lieutenant Governor in Council is authorized to stipulate these definitions as well as exclude any activities for which the legislation ceases to apply.	Agrivoltaics is a novel technology, which can be included explicitly as a normally accepted agricultural practice to integrate the technology in the agricultural sector and reap benefits of it in the province
The Agri-Food Innovation Act	The goals of the Agri-Food Innovation Act [132] in Saskatchewan are: • To promote diversity in the food and agricultural sector of the province; • Assist research and experimentation in the agri-food industry; • Stimulate farmers for the economic growth of the region. Currently, the act signifies that it may support biotechnology infrastructure to achieve its objectives and provide people (especially farmers) new economic opportunities. Similarly, it intends to support sustainable development of the agricultural sector as well as the new skill sets required by individuals associated with agri-food industry as novel technologies evolve. The act allows for the development of bylaws that can promote and help achieve the goals and targets of the act. Moreover, grants can be provided to individuals or organizations and agreements can be signed in order to achieve the act's core purpose.	As the results of this analysis show, agrivoltaics provides substantial economic potential to the residents of Saskatchewan in a sustainable manner and appears to be compliant with the Agri-Food Innovation Act. From the clauses of the legislation, it is evident that initial demonstration experimentations can be carried out for various agrivoltaics in agreement with relevant authorities, which can then be expanded to the commercial scale
The Conservation and Development Act	The objective of the Conservation and Development Act [133] is to help develop and conserve resources related to agriculture in Saskatchewan. The Minister is given the authority to declare any piece of land as a conservation and development area. Moreover, it allows works that can help promote development, subject to the necessary legislative approvals. For such purposes, bylaws can be passed that allow development works.	There are no specific restrictions to the use of solar PV installations on agricultural lands.

Table 6. *Cont.*

Legislation	Description	Relevance to Agrivoltaics
Understanding The Municipals Planning Process in Saskatchewan	The governance structure in Saskatchewan makes local municipalities primarily responsible for carrying out planning and development and managing land utilization. They are able to pass bylaws and establish requirements to allow construction and development works on municipal land. Provincial laws provide authority to municipalities in Saskatchewan to manage the utilization and development of land. The municipalities can set up district planning commissions that help manage land use and its development, and establish policies and regulations regarding land use among associated municipalities. Municipalities can also organize district planning authorities for land management. These authorities can adopt an official community plan or a zoning bylaw [134]. Official Community Plan Municipalities can utilize the Official Community Plan (OCP) and zoning bylaws to formulate a framework defining development targets for regions as well as to implement land use utilization decisions. The main objective of the OCP is to establish a policy framework that facilitates and steers socio-economic as well as traditional and ecological development within the municipality. It can essentially be referred to as a "growth management strategy". So, with the help of an OCP, a municipality may devise targets and aims that can lead and guide the council to manage land within the municipality. Amongst others, the policies addressed in an OCP that have a direct influence on agrivoltaics include: • Existing and probabilistic land use in a sustainable manner; • Existing and upcoming economic development. • Moreover, an OCP may also include: • Policy frameworks for utilization of dedicated lands; • Future development plans; • Maps for existing and future land utilization; • Policy statements for socio-economic, environmental, and traditional development within the municipality • Zoning Bylaws	An OCP can have a direct bearing on agrivoltaics deployment if the legislative framework prohibits any structural work on agricultural land. Hence, consideration is required to introduce the use of agrivoltaics technology in legislation to promote its commercial adoption. According to the Planning and Development Act, among other things, the Minister is authorized to develop policies related to land utilization, approve official community plans, and carry out studies imperative to planning land use in the province. While carrying out land use planning, the government is expected to make certain that provincial interests are integrated into local municipal planning, and vice versa. Thus, agrivoltaics needs to be included as a sustainable development opportunity in the official community plans for future municipal planning works.
	The main regulatory tool for adoption of an OCP is a "zoning bylaw" [135]. A zoning bylaw segregates a single municipality into multiple zoning districts and subsequently manages the newly established districts' development and land utilization. The regulations of a zoning bylaw declare prohibitions and permissions for land usage.	Agrivoltaics can be explicitly included in land zoned for agriculture as per Zoning Bylaws.
	Concept Plans Concept plans are generally developed and included in an OCP. These plans consist of framework to perform further segregation and development as well as suggested utilization of the region. While a municipality is in the process of formulating and approving an official community plan or a zoning bylaw, interim development controls authorize a council to manage development works within the municipality. Through interim development controls, a council assesses, evaluate and either approves or rejects development proposals. Acquiring a Development Permit It is mandatory to acquire a development permit before commencement of work in any municipality that has an existing bylaw. Most of the land use activities are referred to as development and hence, need a development permit issued by a municipality. The proposal submitted for acquiring a permit can either fall under the category of (1) permitted use–any development which is allowed in the bylaw, (2) discretionary use–a proposal which is referred to as a discretionary use (approval of such permits is provided based on the criteria specified in zoning bylaw or, (3) neither permitted nor discretionary use. The third category then requires amendment in municipal bylaws for which an application can be made by the individual or entity seeking a permit for such development works.	To install PV systems on agricultural land, development permits may be required.

Table 6. *Cont.*

Legislation	Description	Relevance to Agrivoltaics
The Planning and Development Act	Now that the general process of municipal planning is reviewed, the Planning and Development Act (PDA) is the cornerstone of the process [136] is described. The PDA defines buildings to be any structure that is built or erected on, in or over a piece of land. Dedicated lands are referred to as lands which are conserved in the larger interest of a municipality, public, environment or as buffer strips of walkways. As per the PDA, development means construction, engineering, or other similar operations on, in or over a piece of land. The main objective of PDA is to organize a planning and development system in Saskatchewan as well as promote sustainable socio-economic and environmental development in the region. The legislation also gives powers to establish official community plans that give control and define usage of land for commercial, industrial purposes, etc. Zoning bylaws can be passed based on official community plans that further specify the terms and criteria for development works. Thus, the PDA has direct bearing on agrivoltaics technology if it is to be introduced in the province. Official Community Plans • A typical official community plan must include the following: • Relevant land utilization legislation of the province • Policies related to existing and future development works • Policies related to management of land considered environmentally sensitive • Provincial level strategies regarding economic growth and environmental management Concept Plan Considering that a municipality has an existing official community plan, a council can make changes to an OCP and approve a concept plan that gives a structure to further segregate a piece of land and carry out development works. A concept plan may consist of suggested use of land (normally for certain fractions of areas); however, any concept plan shall be in conjunction with official community plan. Zoning Bylaws The main objective of a zoning bylaw is to protect the amenities of any region from any sort of land utilization works. A zoning bylaw holds provision to establish districts, defines what types of land use are allowed in a particular locality, establishes a framework for development permits, and identifies what development works do not need permits. For any district, a zoning bylaw may describe land use as either discretionary, permitted or prohibited. Moreover, it can establish criteria as well as performance standards for discretionary or permitted uses of land. It can also identify uses that prohibit buildings from being constructed in a particular area. According to the Planning and Development Act, a zoning bylaw can contain provisions that regulate or forbid development works on the basis of land or resource capabilities or land stability. Similarly, the regulation or prohibition of excavation works and soil removal activities can also be made part of a zoning bylaw. The Planning and Development Act also restricts any sort of development works in districts declared as direct control districts unless the necessary approvals are sought; however, the council can provide exemptions to certain types of development works in that particular district's zoning bylaw. Planning Districts A district planning authority is authorized to use the same powers as the council to develop, manage and implement official community plans as well as zoning bylaws for locations within the district jurisdiction. Regional Planning As per the PDA, a regional planning authority can develop and draft plans that specify land utilization and other development works. The Planning and Development Act later specifies the usage of dedicated lands such environmental reserves, municipal reserves, or public reserves. Each of these provisions can have a direct bearing on agrivoltaics deployment. Special consideration is required in municipal legislation to make the technology conducive for mass adoption.	To diffuse agrivoltaics in the province, the technology should be made part of OCP of different regions in Saskatchewan. The restrictions in Zoning Bylaws provision can have possible bearings on agrivoltaics technology and may act as a deterrent in the future. Therefore, it is necessary that due consideration is given to agrivoltaics technology for its incorporation in provincial planning and development process.

Table 6. *Cont.*

Legislation	Description	Relevance to Agrivoltaics
Dedicated Lands Regulations	The Dedicated Lands Regulations [137] place authority in the Minister to allow a council, which is not an approving authority, to sublease dedicated land (public or environmental) for any permitted use as defined by the PDA, such as for agrivoltaics. However, a council, which is an approving authority, is allowed to do so for municipal or environmental reserves.	-
The Environmental Management And Protection Act	According to the Environmental Management and Protection Act [138], the Minister is responsible for establishing, preparing, and enforcing legislative instruments for the conservation of the environment. The Minister may also authorize research and experimentation works if the Minister deems the activity to be in public interest. Similarly, a relevant permit may be required if any activity is a possible risk to the environment. Moreover, the act allows the preparation of regulations for activities that involve land disturbance for conservation or reclamation purposes.	As installation of PV on agricultural land may raise apprehensions regarding land disturbance, this act holds probable implications for agrivoltaics technology in Saskatchewan.

Provincial Land Act	For the purpose of the Provincial Land Act [139], disposition is a tool through which allotment of provincial land is carried out by means of a transfer, sale, lease, permit, easement or license, which also permits certain activity to occur on that piece of land. Vacant provincial land is a part of land that has not been allotted through any sort of disposition. Through the Provincial Land Act, the Minister can issue a lease, permit, license, easement, or any other disposition. Similarly, the Minister has the authority to categorize vacant provincial land as well as identify the allowed or forbidden uses of such lands. For construction or changes to provincial land, approval from the Minister is again required. According to the Provincial Land Act, the Lieutenant Governor in Council can make regulations with regards to:
	• Allowing the disposition of provincial land (apart from its sale or transfer)
	• For sale or transfer of the provincial land
	    ○ Identifying the class of provincial land that can be sold or transferred
	    ○ Establishing the criteria for sale or transfer
	• Setting out the requirements and criteria for each type of disposition
		-

7. Future Work

The province of Saskatchewan has the highest share of agricultural land in all of Canada. Moreover, it is also leading Canada in per capita greenhouse gas emissions. In addition, due to the amount of solar flux received, it offers one of the most conducive locations for PV installation in the country. Combining the three, i.e., the largest area of agricultural land, highest GHG emissions and excellent solar irradiation, makes the region ideal for agrivoltaic installations. The results of the analysis presented above also indicate the massive potential energy and economic impacts of such a transition. This would not only help the province but also the country and the globe. The earlier this technology is distributed in Canada, the more the Canadian people (farmers in particular) will enjoy its benefits. To this end, there are several areas of future work.

First, additional technical research that provides practical results and evidence regarding crop yield and electrical output is needed, specific to Saskatchewan. This should be carried out with varying crop types such as canola (over 11 million acres), wheat (11 million acres), and lentils (3.7 million acres) in Saskatchewan [140]. Experiments will need to have varying configurations of PV arrays (e.g., vertical racking or tilted, fixed or tracking, optimum inter-row spacing, types of modules, etc.) to identify the best possible combinations for the province's most-grown crops. Research is also needed for supplementary or secondary systems, which can make use of agrivoltaics-based electricity generation such as sourcing pumps and irrigations networks, the processing of crops, the production of fertilizers and fuels such as hydrogen, as well as charging electric vehicles. Another use of agrivoltaics-based electricity could be to source data miners for cryptocurrency or other computing uses (e.g., AI) [59]. There is also great potential of integrating thermal energy from computing/servers, greenhouses and agrivoltaics to energize both facilities [60], which needs to be further investigated. All of these approaches are tangible agrivoltaics opportunities for the people of Saskatchewan, especially the farming community, who could benefit from secondary revenue streams. To harness the full benefits of the technology, however, there needs to be collaboration and coordination between various stakeholders such as funders of energy (e.g., The Office of Energy Research and Development) and agricultural players (e.g., the Ministry of Agriculture).

Agrivoltaics is a relatively new concept to a wide population in North America, and the public is relatively unaware of it but is supportive of the technology once it is explained [64]. Further public education is needed. There may also be a need to reskill traditional farmers and develop programs so that individuals can operate and continue using agrivoltaic systems. The technology has shown positive signs based on the studies conducted in other provinces (Ontario); however, for demonstration to the public and residents, open pilot research is needed. In addition to policy measures that enhance people's knowledge regarding agrivoltaics, it is equally imperative to develop conducive policies and regulations for its widescale adoption. The current legislations and policies of Saskatchewan seem unclear and silent as far as agrivoltaics technology is considered. Existing frameworks may act as a deterrent to the technology or, on the contrary, could be leveraged to promote the technology. Saskatchewan has the largest farm area in Canada and therefore has the greatest potential for agrivoltaics. This technology proposes an additional revenue stream for farmers that might provide better financial security and food security, which is threatened in the region [141]. Statistics indicate that the average age of farmers has increased considerably in the province [142]. Agrivoltaics could be attractive for younger generations to remain involved in agriculture while also providing better economic security and a high-tech environmentally sound source of employment, which are preferred by young people [143]. Agrivoltaic installations on farmland can also be considered protection against inflation since photovoltaic panels are a capital investment [144].

Another dimension to possible future studies includes testing different types of crops for agrivoltaics. Past investigations were performed on a variety of crops including aloe vera [145], aquaponics (aquavoltaics) [146], grapes [147], and the many other crops listed above due to the favorable agrivoltaic microclimate [148]. The results were encouraging as they showed either a very minimal impact on food production or, in some cases, even increased yield of the crops. Enhanced biomass output was mostly noticed for products insensitive to shading or for green vegetables such as lettuce. Experiments may also be performed incorporating different seed spacing over a given area of farmland, thereby ascertaining its implications on different types of crops in agrivoltaic systems.

The light productivity factor is one approach that can benefit agrivoltaic designs in the future [149]. This approach quantifies the efficiency of light distribution, keeping in mind each crop's effective active photosynthetic radiation ranges and the PV system design employed for the application [149]. Some work has been carried out to investigate optimum crop types and PV designs; however, the experiments were performed on a single crop using one array configuration. More work is required to experiment with different iterations of crops and PV designs as there are more than 20,000 edible species of crops produced globally [150]. Moreover, translucent solar PV panels can be installed on greenhouses to facilitate crop growth while simultaneously generating electricity [151–153]. Products used in cultivation such as nitrogen fertilizer [84], anhydrous ammonia [154] or hydrogen [155–157] can be produced by using electricity from agrivoltaics. Furthermore, if agricultural land is situated adjacent to a highway or a main road, then it could be used as an electric vehicle charging port. In addition, more and more people will be inclined towards electric vehicles as the range anxiety phenomenon is curtailed.

The province of Saskatchewan is lagging in terms of the whole of Canada in emissions per capita as well as fossil-fuel-based electricity generation. With more than 61 million acres of agricultural land, the province has huge potential for agrivoltaics. Moreover, excellent levels of solar flux in the region only make it more favorable. The adoption of this technology in the province only promises socio-enviro-economic benefits without any negative impacts on food production. It is a sustainable way of addressing the issue of food and energy for generations to come. Greenhouse gas emissions are already a burning issue in Saskatchewan, and there are new challenges posed by climate change. Agrivoltaics could be one of the answers to these questions, addressing the issue of emissions and contributing positively to climate change efforts.

The current legislations and policies seem unclear and silent as far as agrivoltaics technology is considered. The existing frameworks may act as a deterrent to this technology or, on the contrary, could be leveraged to promote this technology. As reviewed in the current legislation of Saskatchewan, municipalities can play a large role in regularizing agrivoltaics technology. Official community plans and zoning bylaws are the key to any municipal planning and development. They can be used to conserve agricultural land and prohibit any sort of development. Initiatives such as net metering and small power producers' programs can also be molded to include agrivoltaics. The programs could be further incentivized to attract more individuals and entities toward the agrivoltaics business.

It is paramount that both provincial and regional/municipal legislation aligns with regards to agrivoltaics if the technology is to progress in the province. OCPs and zoning bylaws should be prepared as such to promote agrivoltaics deployment in Saskatchewan. Any concerns related to the conservation of farmland should be addressed by ensuring PV-based electric generation does not adversely impact crop growth. The continued use of land for agricultural purposes must be ensured. Although this technology is still in its early stages, it is important to make policies that help its development. There should be added incentives for people adopting this technology, considering the merits it offers to food, energy, and climate issues. Policies and framework aiming to promote this technology should be developed in the future to realize the true potential of agrivoltaics.

8. Limitations

Although this study successfully quantified the potential of agrivoltaics in Saskatchewan related to increased biomass, livestock and electricity generation, there are several limitations. First, experimentation is required to reduce potential errors in yield estimates in agrivoltaic systems in the province. These experiments would give insight into the variation in microclimatic conditions as well as the variability in crop production. Different variations in PV designs (such as vertical bifacial, single-axis or double-axis tracking, fixed and variable tilts, etc.) also need to be experimented with different types of crops. In addition, little research has focused on whether the crops produced under agrivoltaics have the same, reduced, or enhanced nutrient profiles when compared with crops grown using conventional agricultural practices. Moreover, there are capacity limitations and technical challenges associated with the grid integration of solar power plants at these scales, which require further research into the potential necessary transmission and distribution network upgrades as well as the potential for collocating loads (e.g., computing facilities needed to integrate generative AI into the search [158], and other applications).

Next, with the increased production of livestock (sheep in this case), its cost is expected to decrease. This would be expected to increase demand and possible meat substitution (e.g., beef to mutton). An investigation into the market appetite for additional sheep use within Canada as well as globally is needed. This complex economic interplay needs to be more carefully modeled. Future work is also required in order to investigate the environmental benefits of transitioning from consuming cow meat to sheep, considering the impact on human health and the environment. Such a substitution may be environmentally beneficial because beef production requires substantially more resources than sheep production [159] and produces more greenhouse gas emissions according to some studies [160]. To further reduce the environmental impact, the use of rabbits [114] or even moving to a plant-based protein source under PV modules could be explored in more detail. There is also a need to understand the social acceptability of agrivoltaics technology in the region. Hence, a focused effort is required to comprehend the general population's perspectives on both agrivoltaics and increased sheep consumption. Most importantly, farmers' insight and feedback are of prime value if agrivoltaics is to be expanded on a large scale. A detailed financial investigation will be helpful to identify the initial investment for setting up an agrivoltaic system and the rate of return it can offer to farmers. These investigations can further be expanded into developing a comprehensive financial model for an agrivoltaic system, which can be used by the stakeholders and policy makers.

9. Conclusions

Canada, being one of the largest food exporters of the world, has immense potential for agrivoltaics. In this study, the province of Saskatchewan was investigated, which is an ideal region for this technology considering it has the most productive farmlands as well as a high solar insolation. This study yielded significant findings related to technology, agriculture and business for Saskatchewan. The results indicate that by employing agrivoltaics, more than 0.4 million additional tons of wheat could be produced, which could bring in additional revenue of $166 to $220 million CAD based on wheat prices. In addition, 2.9 to 3.5 million tons of additional forage could be harvested in Saskatchewan, which could provide an economic advantage of $273 to $973 million CAD. Furthermore, increased forage yield could be used to graze sheep. The results indicated that between 3.9 million to 4.6 million additional sheep could be grazed on pastureland due to additional forage produced from agrivoltaics. This results in a financial advantage of approximately $731 to $860 million CAD based on high and low values of forage cultivated per acre. Finally, the revenues from electricity generation due to the installation of PVs on farmland and pastureland are approximately $247 billion CAD (vertical PV on agricultural land dedicated to wheat), $367 billion CAD (single-axis tracking on agricultural land dedicated to wheat) and $1310 billion CAD (fixed-tilt conventional PVs on pastureland). It also reviewed the relevant legislations, policies and frameworks that influence implementation of agrivoltaics in the province. This study provided insight to the potential of agrivoltaics in Saskatchewan. Overall, it is evident that agrivoltaics could bring enormous prospective wealth to the province.

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