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Conceptual Design and Rationale for a New Agrivoltaics Concept: Pasture-Raised Rabbits and Solar Farming

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ABSTRACT

Land-use conflicts created by the growth of solar photovoltaics (PV) can be mitigated by applying the concept of agrivoltaics, that is, the co-development of land for both PV and agricultural purposes, to commercial-scale solar installations. In this study, we present a conceptual design for a novel agrivoltaic system based on pasture-fed rabbit farming and provide the technical, environmental and economic analyses to demonstrate the viability of the concept. Included in our analysis are the economic advantages to the PV operator of grazing rabbits at a density sufficient to control vegetative growth, thus reducing the economic and environmental costs of mowing; the dual-revenue stream from the sale of both rabbits and electricity, contrasted with estimates of the capital-investment costs for rabbits co-located with, and also independent of, PV; and the economic value to the rabbit farmer of higher colony-growth rates (made possible by the shading and predator protection provided by the PV arrays and of reduced fencing costs, which are the largest capital cost, by being able to leverage the PV systems for rabbit fencing. We also provide an environmental analysis that suggests that rabbit-PV farming is a pathway to a measurable reduction in agriculturally-generated greenhouse-gas emissions. Our calculations indicate that the co-location of solar and rabbit farms is a viable form of agrivoltaics, increasing overall site revenue by 2.5%–24.0% above projected electricity revenue depending on location and rental/ownership of rabbits, while providing a high-value agricultural product that, on a per weight basis, has significantly less environmental impact than cattle.

1. Introduction

Demand for solar energy continues to grow at an exponential pace, with worldwide capacity expected to reach 1 TW within the next 3–4 years (Haegel et al., 2019). This growth enables the needed de-carbonization of the global energy supply (Goldthau, 2014; Davis et al., 2018). Relentless solar photovoltaic (PV) technical improvements (Pandey et al., 2016; Modanese et al., 2018) have maintained a rapid learning curve (Yu et al., 2011; Trappey et al., 2016; Mauleón, 2016). This in turn has driven down the levelized cost of solar-generated electricity (Branker et al., 2011; Feldman et al., 2014; Barbose et al., 2019), further accelerating solar deployment. The 2018 World Energy Outlook predicts that PV will surpass all but natural gas in total electricity production (IEA, 2018) and the Energy Watch Group predicts 69% of the world's energy from solar PV by 2050 (Ram et al., 2017). Today, PV represents one of the lowest cost sources of power in the world (Eckhouse, 2020).

However, PV growth at this scale will—in the absence of unforeseen technical breakthroughs— require significant physical space (Denholm and Margolis, 2008), creating land-use conflicts between electricity generation and food production (Nonhebel, 2005; Calvert et al., 2013). This challenge will only increase in importance as the global population increases (currently at a rate of 1.08% per year) (UN, 2019), and as nutrition needs grow, with 820 million people already suffering from inadequate nutrition (WHO,

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2018). Despite initial efforts for developing alternative foods that do not need solar flux (Baum et al., 2015, 2016), prior efforts to use crop land for energy as with ethanol have increased the cost of food and increased world hunger for the impoverished (Ford and Senauer, 2007; Tenenbaum, 2008; Brown, 2008).

Agrivoltaics, that is, the co-development of land for both PV and agriculture (Dupraz et al., 2011; Dinesh and Pearce, 2016), represents a viable path forward for solar energy that minimizes land-use conflict, enables electricity generation on open, unshaded land, leverages infrastructure for dual purposes, creates multiple revenue streams, and supports low-carbon sustainable agriculture.

Not surprisingly, states, utilities, and landowners have begun to experiment with practices and policies targeting agrivoltaics that are location and climate appropriate. PV facilities co-exist with emu farming in Australia (REW, 2014), pollinator-friendly sites in Minnesota (Dunbar, 2019), and are supported by myriad incentives, such as the Solar Massachusetts Renewable Target, or SMART program, administered by the state (SMART, 2018). Examples of agrivoltaic theoretical (Dinesh and Pearce, 2016) and experimental research includes aloe vera (Ravi et al., 2016), cherry tomatoes (Cosseu et al., 2014), corn/maize (Amaducci et al., 2018; Sekiyama and Nagashima, 2019), cucumbers (Marrou et al., 2013b), grapes (Malu et al., 2017), lettuce (Marrou et al., 2013; Elamri et al., 2018), and wheat (Marrou et al., 2013b). In addition, some solar sites have begun to use the land between rows for aquafarming (Moustafa, 2016; Pringle et al., 2017), honey production (Amelinckx, 2017), and sheep farming (Quattrolibri, 2009; Ouzts, 2017; Mow, 2018).

This study investigates a novel agrivoltaic concept, which has not been studied in the past: pasture-fed rabbit farming and solar PV. Rabbits are fast growing efficient food converters (e.g. 20% of protein intake into meat (Zotte, 2014)), have low labor and production costs (Amin et al., 2011) and are not land intensive (Goble, 2015), making them potentially excellent matches for agrivoltaics. To analyze this potential, this study provides an assessment of the potential benefits of co-locating rabbits and PV, including a technical, environmental, and economic assessment.

2. Methods

To establish the viability of rabbit-based agrivoltaics, we collected and analyzed a wide range of data, from grazing density to population growth-rates to solar economics to greenhouse gas emissions. These calculations include the role of rabbits in vegetative control (reducing operations and maintenance costs for solar farms), and the role of solar panels in providing shade in reducing animal stress and facilitating high-growth rates for the production of meat.

Our economic analysis of rabbit+solar farms includes the use of existing PV racks as structural support for rabbit fencing, the value of dual-revenue streams (meat and electricity) on a per acre basis, and the environmental impact, including greenhouse gas emissions and water use, of rabbit-solar sites, compared to 1) conventional PV farms, and 2) conventional cattle farming on an equivalent land area. The results are presented and discussed specifically in the context of PV deployment in agricultural regions, where site preparation (e.g., land clearing) is minimal.

2.1. Grazing density of rabbits

Profitable rabbit farming relies on exponential population growth during the summer, but reproductive rates are heavily influenced by food availability and stress, which can be caused by over-crowding, heat and threat from predation. To determine the optimal grazing density of rabbits, we collected data from two sample locations: 1) one in State College, Pennsylvania, which represents the largest rabbit producer in the U.S. (Penn State Extension, 2005) and 2) one in DeForest, Wisconsin, which was previously a research site for a study on the management of pasture-raised rabbits for breeding (Engel, 2012). This latter location provides pasture-raised rabbit data set is used in this study for the base line for yields of rabbits.

To determine the rabbit grazing density the following procedure was used for the two sample locations. First, data from the Web Soil Survey (2019), which details the agricultural potential for a given geographic area in the US, was used to determine the potential forage available for the rabbits. As the exact makeup of the natural vegetation would not be known on a PV site, yields of non-irrigated crops were used as an analog. Specifically, alfalfa hay was used to determine projected tons per acre (4046 m^2) per year of dry matter, D, and where G is the number of days in growing season, total kg wet forage per acre per day, W, is represented as follows:

$$W = \frac{(3.333D/0.00110231)}{G} \tag{1}$$

The number of rabbits (R_a) that can be sustained per acre using the conversion of dry to wet and tons to kg:

$$R_a = \frac{W}{(n \cdot x \cdot m_r)} \tag{2}$$

where, m_r is the mass of rabbits in kg and n is the number of times rabbit eats its body weight per day.

Values are based on the highest density of alfalfa per acre. It was assumed that in the Midwest, 30% moisture is acceptable in dry matter (although in some cases it would need to be lower like baling hay is 15%), the growing season is assumed to be 180 days, no special crop management was assumed. Rabbits can only consume between 2 (n_{low}) and 4 (n_{high}) times their body weight in wet matter per day and the mass of the rabbit is taken as the average doe: 3.2 kg. It should be noted this calculation is a conservative base analysis, as the grazing would be done by young rabbits (fryers) that would be constantly gaining mass and not the mature and heavier does. Rabbits do not graze until weaned, which can be as early as 4 weeks, but could be as late as 8 weeks.[1] If a threshold is set at 4 weeks old or a mass (e.g. weigh at least 0.8 kg (1lb,12oz)) then they are only grazing for 12 weeks and the majority of that time is at a reduced amount of forage intake until they are older.

More rabbits, however, can be sustained in a given area if external food is provided. According to Goble (2015) six square feet (0.56 m^2) are needed per rabbit per day, but this value may be as low as two square feet (0.19 m^2) per doe per day with external feed. The growing season will be assumed to be 6 months, and to eliminate the complexity of variable external feed costs and unknown maximum density factors, the number of rabbits that can be housed on an acre will be determined based only on forage.

2.2. Conceptual design for rabbit-based agrivoltaics

The conceptual one-acre agrivoltaic system design presented

[1] In a conventional rabbitry, the kits should grow to 0.8 kg in 22 days. Most literature states that fryers will grow to ~2.25 kg in 8 weeks. However, this is rarely accurate and it normally takes 9 weeks. Taking that realistic growth rate, they would be of sufficient weight to be grazed at 3.1 weeks, or 22 days. However, weaning/grazing is not recommend at that age for rabbits because their guts are not fully developed. Newly weaned rabbits are the most susceptible to coccidiosis and enterotoxemia, which decreases with age. In general, rabbits can not handle the starches in grasses, especially young, tender grass, until they are at least 4 weeks old. Improperly digested starch is the breeding ground for both coccidiosis and enterotoxemia.

here is 1) expandable, 2) modifiable (geographic latitude), and 3) appropriate for different PV module types and rabbit sub-systems. The design is based on the one-acre plot shown in Fig. 1, which has permanent fencing with a height of 1.1 m (3.6 feet) above ground and extends 0.46 m (1.5 feet) below ground to prevent rabbit escape. To clarify all fences directly in contact with rabbits are buried to prevent burrowing and these fences are not electrified. This would involve trenching, which would increase the capital costs of fencing over a conventional solar farm, but would be expected to be relatively inexpensive on agricultural land (and would be identical to the costs of a rabbit farm). The outer fence has two sections 65.7m long and two sections 60.1m long, which are along the length and width of the farm. This fence is electrified.

The conceptual solar farm has eight double rows of 128 modules each of 60-cell crystalline silicon 300 W solar (JinkoSolar, 2019) with a 30-degree tilt angle geometry shown in Fig. 2. Rows are spaced 5 m apart to ensure no row-to-row shading according to shading calculations shown in Appendix A. Each PV module has a peak rated capacity of 300 W. The site design includes 1048 modules with a peak capacity of 314 kW. This will be the 1 acre building block size of the agrivoltaic farm. So, for example, 5 acres (sections) would be enough to employ a full-time rabbit farmer and would provide 1.57 MW of PV.

Unlike a conventional solar farm, two sets of additional fences are needed for a rabbit agrivoltaic farm. First, there are eight fences under the front of the solar panel rows in each acre, which are 63.5 m long (short side of the rack) as shown in brown in the partial assembly shown in Figs. 3 and 4. Each of these front PV rack fences could be manufactured in a line or separated into 15 smaller fences based on the distance between solar mounts. In both Fig. 3 (front side cut away view) and 4 (back side cutaway view) the external fences are shown semitransparent. The exterior fence (not buried) is an electrified fence to discourage ground predators. The permanent internal fences are shown in brown, which represents buried fences with light shields to discourage burrowing/digging at the locations.

Finally, there are yellow fences shown in Figs. 3 and 4, which represent movable fences.

The system has four moveable fence sections that can be used to corral the rabbits from one area to the next. Rotating the rabbits by sections of the PV rows every day (as shown in Fig. 5) is hypothesized to facilitate high colony growth rates, due to previous experiments with small rabbit farms (Engel, 2012). Under this scheme, the rabbits gain access to fresh forage and provide weed control for the PV. Fencing (brown in Figs. 3 and 4) is fastened to the PV frames creating inter-row corridors or aisles. The rabbits can work each section of corridor with daily rotations throughout the

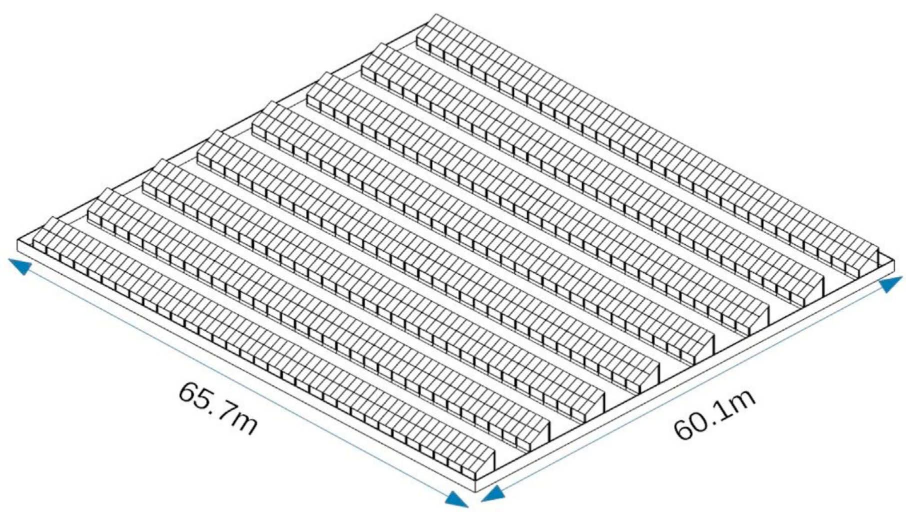

Fig. 1. Ortho view of 1 acre 314 kW solar agrivoltaic rabbit farm building block.

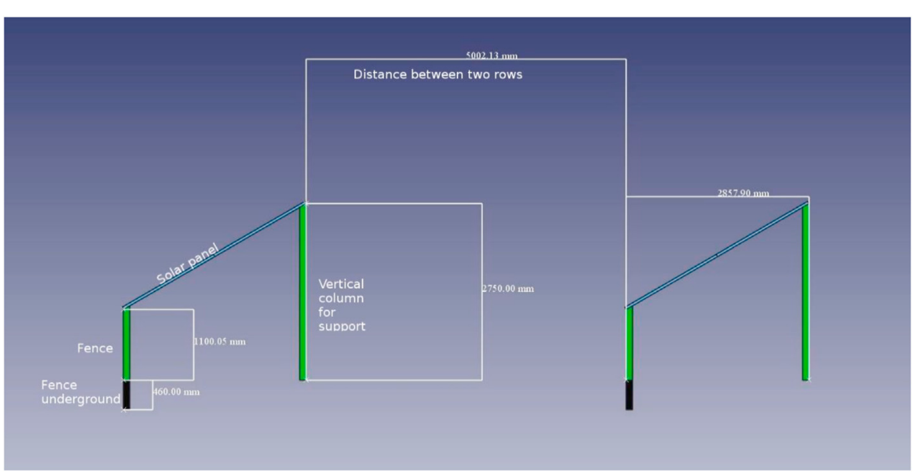

Fig. 2. Side view geometry of two module racking system set at 30° tilt angle for the solar agrivoltaic rabbit farm.

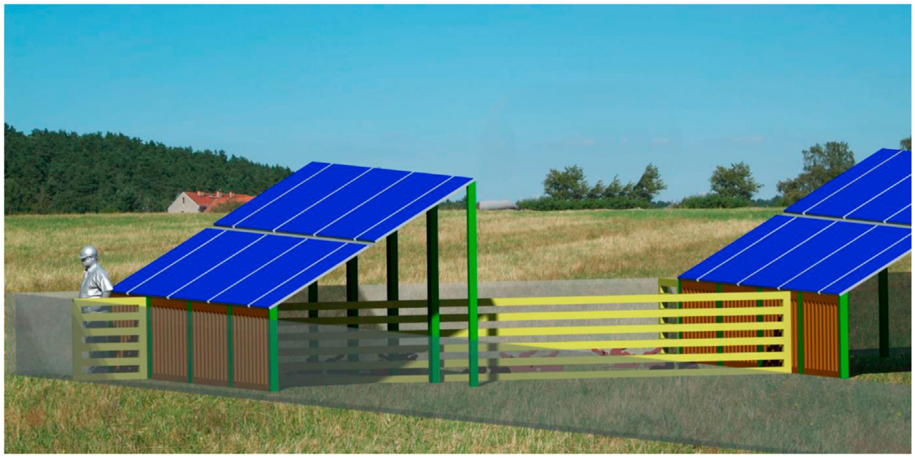

Fig. 3. Front side of cutaway section of rabbit agrivoltaic sections showing permanent fences (clear for exterior and brown for rack fences) as well as movable fences yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 4. Back side of cutaway section of rabbit agrivoltaic sections showing permanent fences (clear for exterior and brown for rack fences) as well as movable fences yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

growing season as shown in the top view of Fig. 5. Males and females are separated to control reproduction, optimize growth and reduce overall stress.

As seen in Figs. 1 and 5, the pasture has a permanent fence in one direction, ideally east-west for solar output so that the spacing between rows of PV become the corridor. The slots on the bottom of the fence are no larger than 5 cm × 5 cm to avoid rabbit escape if rabbits are bred offsite (if on sight the fence would need to be smaller 5 cm × 5 cm hoes to contain 2–3 week old kits), so standard chain link fencing is appropriate. Crosspieces to subdivide the rows would be made out of the same type of fencing material but can be repositioned by the farmer, depending on the previous day's grazing activity. Overall, the four movable fences have a height of 1.1 m and are 7.7 m long (which can be moved in sections). There are also short sections of movable fence or gates/doors connecting each row to the outer fence. The outer fence is electrified with a small solar powered system to discourage ground predators. Rabbits are never left in these corridors as they are rounding the corners as the electric exterior fence is unlikely to contain them because of their burrowing ability.

2.3. Pasture-fed rabbit operations

The pasture-fed agrivoltaic rabbit farm is developed with the following assumptions:

1. New Zealand, California, or a cross of the two breeding female rabbits (does) and male rabbits (bucks) will be off-site and provide offspring for the agrivoltaic site. Only juveniles will graze and they will be separated by sex using four movable fences. Note: The calculations only consider the pasture-grazed rabbits. Breeding pairs could provide offspring from another company, be off-site owned by the pasture-fed rabbit enterprise, or be located indoors on site.
2. Rabbits will be moved once daily as shown in Fig. 5.
3. Rabbits will breed in batches, not on a rolling basis, with offsite breeding enabling reproductive control. Breeding will be synchronized so that the greatest population density on pasture aligns with peak pasture production. For example, one can control the breeding cycle so that all 40 does give birth,[2] i.e., kindle, at virtually the same time so all their offspring are weaned ready to go out on pasture as a group. This cohort will then be sent for processing and preparation will begin for the next round of kindling. Slaughter will be outsourced.
4. Light-weight portable shelters will be put in place by the farmer in addition to the shade provided by the PV panels as protection against aerial predators.

[2] 40 is based on breed-back capacity and on a single farmer's capacity of breeding 4 does per week on a rolling basis.

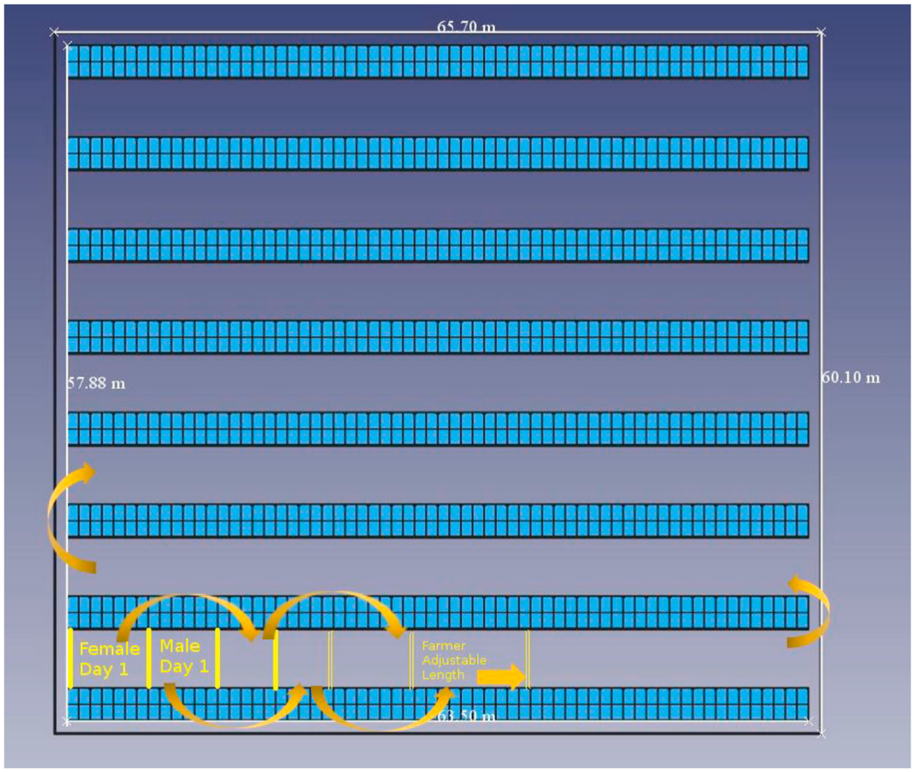

Fig. 5. Rotation schedule, where the yellow solid lines indicate 4 movable fences that are used to move rabbits from one section in a row to another, hollow lines indicate potential variable locations of the fences, which are based on the previous day's grazing activity. Curved arrows indicate daily rotation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. To avoid re-infecting an animal from parasite larvae, it is recommended not to re-graze an area for at least 28 days. Thus, the grass is cut in between the rows of PV modules monthly by the rabbits, which would be similar to $1\times$/month mowing. This will maintain pasture health, while also eliminating the opportunities for weeds to gain a height large enough to interfere with the PV system.
6. Rabbit farmers will adjust the spacing between movable fences to preserve the ability of the pasture to regenerate (e.g. do not let the animals take plants down below 10 cm) Alternatively, the rabbits could be employed to control a weed invasion by remaining in place and grazing to the ground.
7. Rabbits can survive on pasture alone, but the average grow-out period for a fryer is twice the industry standard: 16 weeks as opposed to 8 weeks. This assumption again ensures the calculations in this study are conservative as most rabbit farmers at least partially supplement pasture-raised rabbits with additional sources of food to optimize economic output.

Using these seven assumptions, a sensitivity is run on the pasture fed (minimum number of rabbits that can be sustained).

2.4. Economic analysis

2.4.1. PV operations and maintenance

The cost to control vegetative growth that can impede access, deposit particulates on module surfaces and create unwanted shading of PV systems, varies widely. The most common method of weed control is mowing although spraying herbicides is also used it must be done repeatedly over time and there are environmental concerns associated with herbicides (Movellan, 2014). The conventional method for vegetation management includes as much as six herbicide applications costing $40-$100/acre for each application and mowing that can cost more than $50/acre (Kraushar, 2017; Naturchem, 2019), requiring detail work around the arrays, with some risk of collision damage. The additional savings accrued by not having to mow a site, however, are hard to calculate as they reflect local vegetation and climate, which determine growth rates; the height of panels above the ground also influences mowing needs and the type of equipment required. However, calculating deferred mowing costs provides a value for the operations and maintenance reductions that may be possible with pasture-fed rabbits. Rabbits 'trained' to graze, without additional feed provided, usually clear 90−95% of the vegetation in their pasture area. Yet, some vegetation management may be required to cut remaining and to encourage sufficient regrowth of all species.

The revenue generated by a PV farm is also highly dependent on a shifting commodity market. For electricity generation, we looked at an average power purchase agreement (PPA) from (Bolinger and Seel, 2018), which for utility-scale PPAs in the range of $0.02/kWh-$0.04/kWh based on as sample of 232 contracts.

PV electricity output for the two locations was calculated with the Solar Advisory Model using the design factors listed above such as the 30-degree tilt angle and 14% system losses, and standard assumption on interannual variability (Dobos et al., 2012; Ryberg et al., 2015).

2.4.2. Economics of rabbit farming

Rabbits are generally slaughtered at 5 pounds (2.27 kg) live weight (plus or minus 4 ounces or 0.11 kg), which yields an average of 2.7 lb (1.22 kg) carcass (Engel, 2012). Cleaned and processed rabbit meat is regularly sold to the U.S. consumer at $13/lb or about $40 per rabbit (Fossil Farms, 2019; igourmet.com, 2019; White Oak Pastures, 2019), although prices can vary based on the quality of meat (i.e. grass-fed, pasture-raised, and organic). Rabbit fur also is sold for about $5/rabbit (Black Bear Haversack, 2019). In addition, the marketing appeal of low-polluting, solar-farmed, pasture raised rabbits should not be overlooked and is likely to add value. As these rabbits would most likely have premium value, we estimate that the total revenue for a solar rabbit could be as high as $45, assuming the solar farm operator also farms the rabbits. The alternative is that the solar farm operator rents the land to a rabbit farmer. Although there is variability in rental costs due to land grazing quality, 1 acre of land in Wisconsin averages $32 a month and land in Pennsylvania averages $25 a month to rent (Voth, 2018). These values are used over the assumed 6 month/year rabbit farming season although rental rates for pasture can be lower in other states (e.g. MI is $13 (Netwon, 2019)).

2.5. Sustainability/carbon benefits of PV+Rabbits

To gauge the sustainability of the rabbit agrivoltaics they will be compared to 1) conventional PV farms and 2) conventional meat farming (cows). All farms have an equivalent land area as for the agrivoltaic system.

PV has long been considered a major contributor to sustainability for a high-tech electricity-driven society (Pearce, 2002). Life cycle analysis has shown that PV has energy pay back times in less than five years even in low solar flux locations (Laleman et al., 2011) and careful analysis shows that PV has an excellent ecological balance sheet (Fthenakis et al., 2005). PV systems have grown steadily that today, a large fixed tilt PV plant like the agrivoltaic system designed here, but covering 2.8 acres will produce 1 GWh per year (Hardesty, 2013). As PV is a major net energy producer (Pearce and Laue, 2002) if it is used to replace fossil fuels PV can substantially reduce greenhouse gas emissions (GHG). Life-cycle analyses show that the CO_2 emissions produced by the manufacturing, transportation, installation and maintenance of PV systems range from 16 to 40 gCO_2/kWh (Turney and Fthenakis, 2011) resulting in significant fewer carbon emissions than energy production from coal, which produces an average of 909 gCO_2/kWh (USDE, 2004) in the US. PV is also a far more efficient use of land for climate-neutral energy production compared to the combined use of coal and the best carbon capture, carbon sequestration and biosequestration methods available (Groesbeck and Pearce, 2018). However, clearing land for PV does represent an ecological impact (e.g. removal of vegetation) (Turney and Fthenakis, 2011) that could be avoided if agricultural land is converted to a pasture-fed rabbit agrivoltaic system.

In addition, it is well known that conventional meat production has a large carbon footprint (Nijdam et al., 2012). To raise one cow-calf pair, requires 1.5–2 acres (NRCS, 2009) and a considerable amount of water. Depending on the farming and slaughtering methods, to produce one pound of beef may require more than 1900 gallons of water (BCRC, 2019), a number that includes the irrigation needed to maintain grass fields for grazing. Beef cows typically range in size from 1000–1500 pounds (450–680 kg). If a 1000-pound cow is raised and slaughtered, 430 pounds of meat will be sold (USDA, 2019). The average age for a beef cow to be slaughtered is 18 months (GRACE Communications Foundation, 2018). By the time a cow is slaughtered, it will have produced 105–180 pounds of methane (FAO, 2006), which is a potent greenhouse gas (GHG). For purely pasture-raised cows, the food they eat is less energy-dense than industrially raised cattle and therefore it takes them longer to mature to slaughter weights (GRACE Communications Foundation, 2018). Besides methane, 17 billion pounds of nitrogen fertilizer is deposited on feed crop fields covering 149 million acres across the United States, which produces copious amounts of nitrous oxide (EWG, 2011). The removal of trees and entire tropical rainforests across the world to allow for cow grazing and production of feed crops accounts for 2.8 billion metric tons of CO_2 emissions every year (FAO, 2006). In North America, a cow consumes 75–300 kg of dry matter to produce 1 kg of protein (Walsh, 2013).

These values are used to determine the greenhouse gas emissions changes from reductions in methane emissions and forest clearing, area per unit kg of protein and water use reductions for moving from cow-related agriculture to pasture-based rabbit agrivoltaics are quantified.

3. Results and discussion

3.1. Technical performance of rabbit agrivoltaic systems

Electricity generation per acre from the 30-degree tilt angle 314 kW PV array described in section 2.2 would produce over 381 MWh and 433 MWh per year, in PA and WI, respectively.

Using the method outlined in section 2.1.1, it was found that, in State College, Pennsylvania, 2–5 pasture-fed only rabbits could be sustained per acre per cycle. In Deforest, Wisconsin, it was found that 5–11 rabbits could be sustained per acre of pastureland per cycle. With three cycles available per year, Pennsylvania located agrivoltaic farms could house 6–15 rabbits per acre and Wisconsin agrivoltaic farms 15–33 rabbits per acre per year. These numbers represent the number of rabbits that can be sustained using only what grows on site with no supplemental food sources.[3]

3.2. Economic performance of rabbit-based agrivoltaic systems

The total annual gross revenue from an acre of the PV farm can vary widely based on the price of the solar electricity and annual irradiance. Here it is assumed that the solar-generated electricity is sold via PPA contracts. Using the values assumed above rabbit agrivoltaic systems would provide PPA revenue per acre ranging from $7623-$15,247/year in PA to $8678-$17,358/year in WI. Considering a one-acre could support 314 kW of PV and the costs for PV farms would need to have a capital cost under about $1/W installed to provide profit at the PPA rates used. This means that any savings from O&M or additional revenue gained from rabbit sales would bolster agrivoltaic economics. Table 1 summarizes the revenue generated by the dual use of land for PV and rabbit production.

Table 1 shows that if rabbits are effective grazers, the avoided costs of mowing could result in 1–8% increase in revenue (that would go directly to profits) for the PV farm. Thus, this may be worth simply allowing an outside firm to farm rabbits on the premise for free. The rabbit firm would provide the fencing, labor, and supplies needed to farm the rabbits. As rabbit farmers currently need to rent or own the land they use there may also be rental fees possible. Simply renting out the agrivoltaic PV array could also be financially beneficial ranging from 2.5% to over 10% in PA and 5%–19% in WI. A single farmer could handle a few hundred rabbits so in the model proposed here could cover several dozen acres of a large-scale solar farm. At the same time, these rabbit farmers could be trained to perform basic maintenance on the PV or to notify others if problems are observed. In the land rental case there would be no increased capital costs for the solar asset owner.

[3] If external feed is provided the Goble method provides for 7225 rabbits/acre and for the even more intensive Engel assumption a total of 21,294 rabbits/acre could be maintained. Although having 20,000 rabbits in a single large colony supported by external feed may not be supported by the social structure of the rabbits, resulting in bullying behaviors.

Table 1
Revenue generated with dual use of land in one acre of farm for rabbits and 314 kW of PV.

Source of Revenue		Pennsylvania (6–15 rabbits/acre/year)		Wisconsin (15–33 rabbits/acre/year)	
		Annual Revenue/acre (in 1st year)	Percent of PV Revenue	Annual Revenue/acre (in 1st year)	Percent of PV Revenue
PV	Solar Electricity	$7623-$15,247	–	$8678-$17,358	–
Cost Savings	Reduced O&M Costs	$240/acre-$600/acre	1.6%–7.9%	$240/acre-$600/acre	1.4%–6.9%
Increased Revenue	Rabbit Revenue Grass Fed Only	$270 - $675	1.8%–8.9%	$675 - $ 1485	3.9% –17.1%
	Land Rental Only	$150	1.0%–2.0%	$192	1.1%–2.2%
Totals	Total Increase if Self-farm	$510-$1275	3.3%–16.7%	$915-$2085	5.3%–24.0%
	Total Increase if Land Rent	$390-$825	2.5%–10.8%	$867-$1677	5.0%–19.3%

In some cases, as seen in Table 1, the revenue for the rabbit farming may make up a significant percent (up to 17%) of the revenue from the PV site, which jumps up to 24% if the O&M costs reductions are counted as well. In such locations, as in Wisconsin with high rabbit production rates shown here, PV operators may wish to invest in the additional fencing, supplies and labor costs in order to acquire a greater share of the rabbit revenue by running the rabbit fraction of the agrivoltaic system themselves. Future work is needed to determine the full costs (labor, materials) for preparing an agrivoltaic system to the design specifications provided here. It should be pointed out, however, that as there are commercial pasture fed rabbit farmers presumably making a profit from providing all of the fencing and shading with capital costs that the agrivoltaic system should be more economically competitive as the most expensive components (ground mounted poles for the fence and partial shading) are already provided for with the PV array. Future work is needed to determine the optimal business model from the two proposed here (self-farm or land rent) for a PV farm owner to benefit from the integration of rabbits on the PV site as well as test this method experimentally and determine full costs.

Finally, from Table 1, it can be seen that the annual revenue for the PV system operator is increased if rabbits are grazed between the rows on a 1-acre farm in the first year. Over the span of 25 years, the efficiency of solar PV farm will decrease each year for the majority of modules by 0.5%/year (Jordan and Kurtz, 2013), which will tend to increase the percent of revenue coming from rabbits. This makes Table 1 percentages all conservative, which will have a positive effect on the levelized cost of the electricity from the farm. This would tend to increase the percent of revenue due to rabbits if their selling prices remain constant although the stability of rabbit value into the future is largely unknown.

3.3. Social synergies

3.3.1. Agrivoltaics versus PV land use

Beef consumption is on the decline in America (NRDC, 2017), likely as a consequence of increasing awareness of the environmental, climate, and health impacts of consuming beef. Yet food consumption is a cultural activity (Carolan, 2016a, 2016b) and any attempt to understand or shift food consumption requires attentiveness to food as cultural. Given the supportive public perceptions of mixed-use agrovoltaics, future research should prioritize understanding the opportunities and barriers associated with increasing market penetration of rabbit meat; this research could work to address issues associated with siting and production or could focus on market issues and social perceptions affecting restaurant utilization of rabbit meat. As stated above, a community approach that seeks to understand perceptions and values in order to further development that aligns with social priorities is likely to elicit supportive responses to future development (Prehoda et al., 2019).

Recent research suggests that utility scale solar development is less socially acceptable than commercial scale wind projects (Firestone and Kirk, 2019). However, it is important to note that the survey sample for this study includes respondents who have wind energy facilities sited nearby their communities, suggesting a potentially more important finding: people who have experience with renewable energy technologies are more supportive of those technologies. This is supported by other research (Sherran et al., 2019) and suggests the importance of incremental renewable energy development spread throughout communities, because visibility and exposure appear to increase support. Projects that engage community members in discussions of project development with an attentiveness to the community concerns can contribute to successful solar outcomes (Prehoda et al., 2019). Many groups that hope to promote solar development have already begun to utilize agrivoltaics in marketing and outreach materials (Feedstuffs, 2019; REC Solar, 2019). Preliminary data indicates that 72% of respondents to a survey on preferences for mid-to large-scale solar development on Long Island ($n = 295$ of 405 respondents) are more likely to support a project if it is designed to provide a supplemental income for farmers on Long Island (Schelly et al., forthcoming, see http://solarroadmap.org/). Motivations for solar adoption are well known (Schelly, 2014a, 2014b; 2015a, 2015c) and include environmental and economic considerations but also concerns about the distribution of benefits associated with solar development. Projects can explicitly address the possibilities to promote commercial scale solar development through a better understanding of social values and preferences, including preferences for solar projects developed in mixed-use agricultural settings that provide additional income to farmers.

3.3.2. The impact of agrivoltaics on animal welfare and rabbit markets

Although rabbit is considered a specialty meat in the US, at least ten large and more than 40 local grocery store chains carry rabbit meat (Rabbit Advocacy Network, 2015). Many farms sell directly to consumers or through online wholesale vendors where a variety of rabbit cuts and products are available (Fossil Farms, 2019; igourmet.com, 2019; White Oak Pastures, 2019). A review of online farm forums suggests that most sales are small scale and at local levels.

Despite the production opportunities for rabbit meat showcased by several countries in Europe, the U.S. has been hesitant to embrace rabbit meat (EU, 2017). In 2015, Whole Foods stopped selling rabbit meat due to pressure from animal advocates, concern over rabbit quality of life in cages, and potential issues with low sales volume in their pilot markets (Nguyen et al., 2015). Before halting the sale of rabbit meat, Whole Foods investigated and published several documents describing the animal welfare standards that would need to be met by meat producers (Whole Foods Market, 2013a, 2019b). When overseen by experienced rabbit farmers, the pasture-raised agrivoltaics system proposed here would far surpass the industry standard of quality of life for rabbits and thus remove the primary impediment to rabbit meat being sold at Whole Foods and other markets that cater to ethical eaters (Johnston et al., 2011).

3.4. Environmental sustainability

The results of this study make it clear that a rabbit agrivoltaics represents a more environmentally-responsible farming method than traditional cattle raising and can also help justify the placement of solar arrays on open fields, thus obviating the need for tree removal. The latter practice accounts for 36 g CO_2/kWh, which adds to the carbon footprint of an otherwise extremely environmentally-friendly method of energy production (Turney and Fthenakis, 2011). If a PV system is installed in a farm field where trees do not have to be removed, this extra carbon production is not a factor.

The results of this study have also shown that the combination of rabbit production and solar produce lower costs as a symbiotic agrivoltaic system. These cost reductions could be used to reduce the cost of both, solar electricity or they could be used to reduce the cost of rabbit meat. If these cost reductions are used to reduce the cost of rabbit meat it would provide a further financial incentive to increase the market share of rabbit compared to other animal proteins such as beef. Thus, the known environmental benefits of solar PV can be increased further if the rabbit meat is used to offset beef as a source of human protein. Although it should be noted this conversion would demand social acceptability, which necessitates future study to determine the viability of this approach on a regional basis as this varies considerably both internationally and among groups within a nation. Small herbivores, such as rabbits, produce a negligible amount of methane (Franz et al., 2011) when compared to a typical beef cow, which produces 105–180 pounds of methane in its lifetime. A standard rabbit has also been shown to produce an average of 3.6 kg CO_2 eq/kg live weight, which is similar to the CO_2 emissions from pigs, but significantly less compared with those of beef cows (Cesari et al., 2018). A single cow produces 70–120 kg of CO_2 per year and the slaughter and processing of 1 kg of beef produces 34.6 kg CO_2 (FAO, 2006). Thus, the GHG gas emissions per kg of meat is reduced by more than an order of magnitude converting from cows to rabbits. It is clear that the climate-related environmental benefits of raising rabbits instead of cattle are substantial and that as consumers become better educated about climate change their source of protein preferences may shift (Laestadius et al., 2016). Although it should be pointed out that a plant-based protein source would be better for the environment than the rabbits. Considering a worst-case scenario, an acre of rabbit agrivoltaics supporting the highest density of rabbits investigated here (33/acre) with a mass of 3.2kg/rabbit each acre would produce 380 kg CO_2 eq. These carbon emissions would be dwarfed by the carbon offset by the PV system by supplanting fossil-fuel power generation with solar power generation. By combining a low-carbon method of electricity production with a low-emissions farming operation, both the PV system and farming operation become greener. Future work is needed to perform a complete life cycle analysis on the system to determine rabbit agrivoltaic sustainability, however, based on the reduction in carbon emissions for the synergies observed here in the system it out performs conventional sources of meat.

3.5. Scaling rabbit-based agrivoltaics

Rabbits are raised in the U.S. for meat, Angora wool, hides, breeding stock, for show and for laboratory use. According to the 2017 Census of Agriculture (NASS), more than 4000 farms sold over 495,000 rabbits nationally in the U.S. There are rabbit farms in every state, with Texas having the most farms and highest rabbit production (NASS, 2017). Rabbit farming is more sizable globally with an estimation of over 800,000 tons of rabbit meat produced annually (Lebas, 2009; Zoltan et al., 2017). The largest sources of rabbit production are Western Europe (~600ktons), East Asia (~600ktons), Eastern Europe (~300ktons) and North Africa (~100ktons) (Lebas, 2009; Zoltan et al., 2017). The annual consumption of rabbit meat varies widely. In the U.S. only about half of people have tried it and in a 2004 study only 23% would be willing to buy it making it a niche market (Beal et al., 2004). However, in other locations eating rabbit meat is quite common. For, example the French average consumption is 3 kg/capita and in Malta the average consumption is 9kg/capita (approx. 9 kg/capita) (Lebas, 1992; Colin and Lebas, 1996). The current level of rabbit farming globally indicates that there is ample opportunity to scale rabbit-based agrivoltaics both in the U.S. and globally on existing rabbit farms as well as potentially offsetting more carbon-intensive cattle.

3.6. Future work

Several areas of investigation are needed to fully realize the potential of rabbit-based agrivoltaics. First, the assumptions described in section 2.3 need to be validated in an experimental setup to prove that rabbit farming can obtain the expected yields while not negatively impacting PV production in unanticipated ways. Thus, for example, the impact of partial shading on the species the rabbits are eating as a function of location must be studied in future work. There is not a straightforward relationship between shade and yield. Although it is known that PV-related shading can increase yields on some plants (e.g. lettuce) the partial shading from the PV could reduce some of the rabbit feed crops, reducing the yield per acre. In addition, the susceptibility for weed growth not eaten by rabbits requiring additional mowing or herbicide application for a given pasture needs to be tested over a wide range of locations. Such experiments could be performed on a retrofitted existing solar farm (although it should be noted that installing fencing could be challenging). In addition, data is needed to understand predation risk and to design appropriate air-predator coverings that may deter birds of prey while also capturing reflective light that can increase power output from the PV arrays (Andrews et al., 2013, 2015). The impact of only using partial low-concentration on the PV system performance should be quantified. In addition, the ability of rabbits to effectively provide weed control for PV in different growing conditions and with different mixes of crops should be tested on farms throughout the world. Rabbits have very small mouths that can precisely choose a single blade of grass and eat it down to the crown and may therefore selectively eat their preferred species while allowing less palatable species to flourish. A balance will need to be found in the appropriate plants based on the operating climate for locations throughout the world considering rabbit-based agrivoltaics. The yields of rabbits in such systems will provide better data on both the O&M cost savings as well as the revenue and costs of rabbit farming, all of which can be validated by future experimental work for systems located throughout the world. Lastly additional work is needed to quantify the sustainability of this approach and its social acceptability. The social acceptability must be determined for consumers to purchase solar-raised rabbits for food consumption as well as for farmers to enable agrivoltaic systems to be developed on their land. These social acceptability studies need to be performed at the regional level.

4. Conclusions

Transitioning from fossil fuels to a more solar-intensive energy portfolio with large area requirements, is likely possible by re-imagining solar as a dual-use opportunity. This study found that rabbit and PV co-development have multiple synergies including: 1) reduced O&M costs of rabbit-inhabited solar farms on the order of 1.4%–7.9% of solar revenue/acre, 2) economic gains (the revenue from either the sale rabbits or land rent) ranged from 1 to 17.1% of solar revenue/acre, and 3) cost savings for rabbit farming by using existing PV ground mounts as structural support for fencing (the largest capital cost for high-intensity rabbit farming as well as shelter provided by the PV to protect rabbits from airborne predators as well as too much sun exposure). Finally, rabbit agrivoltaics may increase social support for PV deployment on existing farmland and expand market demand for rabbit meat in the U.S. Future work is needed to verify these synergies experimentally as well as determine the effectiveness of solar-rabbit farms in moving the US to a less carbon-intensive economy.

Disclaimer

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Declaration of competing interest

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

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Appendix A. Shading Calculations

Row spacing to ensure no row-to-row shading according to shading calculations where a distance, d_{row} is:

$$d_{row} = [\sin(a_{tilt})\, xM]/\tan(a_{alt})\, x\cos(a_{az-S}) \tag{3}$$

where M is the total module height (in this case 3.3 m as two modules are stacked vertically), a_{tilt} is the tilt angle (30°), a_{alt} is the altitude angle on December 21st at 9:00 a.m. (15.5°), and $a_{az\text{-}S}$ is the difference between azimuth angle on December 21st at 9:00 a.m. A and due solar south (42.5°). These values were calculated at a latitude of 38°, which is roughly the latitude of Washington, DC in the middle of the U.S. The value for d based on these values is 4.4 m. As the systems were installed north of 42.5°, 5 m of row spacing was given to ensure maximum coverage of the available land area. This is in line with commonly used industry value of:

$$d'_{row} = 3x\,[\sin(a_{tilt})\, xM] \tag{4}$$

d_{row}' has a value of 4.95 m, which is beneath yet close to the more conservative 5 m row spacing selected.

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