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The potential for fencing to be used as low-cost solar photovoltaic racking

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ABSTRACT

Popular agrivoltaic systems use photovoltaic (PV) farms for pasture grazing animals. In general, these agrivoltaic systems do not reduce the capital cost of a PV farm and in some cases can increase it. To overcome this challenge this study investigates the potential for retrofitting existing animal fencing on farms to have dual use for vertical-mounted monofacial PV racking. Specifically, this study catalogs types of fences and wind load calculations classified under Risk Category I are run through a new python-based Open Source Wind Load Calculator to determine the viability of fence-based racking throughout the U.S. The base shear force for all the fences are calculated for a range of wind loads from 80mph to 150mph (129 km/h to 241 km/h) and the results are mapped to indicate the number of PV modules between the vertical fence poles a fence can tolerate in a specific location. The results show the required fence type including post and battens in a given area for sheep, goats, pigs, cows, and alpaca to be used for agrivoltaics. Overall, at least one PV module between posts is acceptable indicating a new agrivoltaic system potential that as little as \$0.035/kWh for racking on existing fencing. Although the yield for a vertical PV can range from 20 to 76 % of an optimized tilt angle depending on azimuth, the racking cost savings enable fence-retrofit agrivoltaics to often produce lower levelized cost electricity. Future work is necessary to determine the full scope of benefits of vertical PV agricultural fencing on a global scale.

1. Introduction

Agrivoltaics, which is the co-development of land for both solar photovoltaic (PV) electrical production and agriculture is a rapidly growing field under intense investigation throughout the world (Dupraz et al., 2011; Dinesh & Pearce, 2016; Aroca-Delgado, et al. 2018; Zainol Abidin et al., 2021, Pearce, 2022). In addition to growing crops, agrivoltaics is used for animal food-based production. Perhaps the most straight-forward application of agrivoltaics is to plant pollinator-friendly crops at PV farms for honey production (Amelinckx, 2017). There can be complex synergies. For example, PV-created partial shading delays bloom, which increases floral abundance during the late-season for pollinators in a dry land (Graham, et al., 2021). PV in such agrivoltaic systems can even be used for pollinator conservation (Dolezal, et al. 2021). Agrivoltaic systems also can make use of grazing animals to reduce or, in the optimal case, eliminate the need for herbicides and/or grass cutting on solar farms (Handler & Pearce, 2022). This not only has the obvious improvement in negative environmental impact of chemicals synthesis, use and disposal, but also reduced greenhouse gas production for fueling cutting. Grazing-based agrivoltaics also reduces operation and maintenance (O&M) costs (and module breaking during mowing) so there have been many approaches proposed. Agricultural practices for producing meat can be mundane like providing shading for cows (Sharpe, 2020). These agricultural approaches can also be exotic like pasture-based rabbit farming (Lytle et al., 2021), which is considerably more environmentally friendly than other larger animal forms of meat production. The most popular animal-based agrivoltaic systems are for pasturing sheep (Quattrolibri, 2009; Mow, 2018; Andrew et al., 2021a). Andrew et al. found that although solar pastures produced 38 % lower herbage than open pastures due to low pasture density in fully shading beneath PV, this was offset by higher forage quality, resulting in similar spring lamb production to open pastures (Andrew et al., 2021a; Andrew et al., 2021b). Land productivity can be greatly increased because the sheep grazing is constant while substantially more value is generated by the PV. The PV also provide benefits for the animals by offering shading from the sun (e.g. better wool for sheep) and the animals prefer PV-cast shade (Maia, et al. 2020). Finally, agrivoltaic has substantial social benefits. Solar developers are open to the idea of agrivoltaics (Pascaris et al., 2021b) as are farmers (Pascaris, et al., 2020), and the support of the general public for agrivoltaics may help

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Fig. 1. (a) Multi wire, multi batten type fence; (b) Multi post multi wire type fence; (c) Pig fence netting; (d) Chain link type netting/mesh.

Table 1
Fence type and wire specifications (Gregory, 2019; Bucklin et al., 2018; CLFMI, 2014;Colombia, 2015).

Wire Specifications								
Farm type	**Fence Type**	**Fence Height (m)**	**Post spacing (m)**	**Wire spacing**	**Wire Type**	**Wire size (mm)**	**Tensile strength (MPa)**	**Recommended Tension (N)**
Sheep	Wire with battens	1.05–1.20	4.0–5.0	8 wires	Steel HT	2.5	413–1378	1471
						3.15		1961
Goat					Mild	4	350	2451
	wire with posts	1.05–1.20	5.0–10.0	9–10 wires	Steel HT	2.5	413–1378	1471
						3.15		1961
					Mild	4	350	2451
Pigs	post & mesh	0.90–1.00	3.5–5.0	wire mesh	HT	1.6	413–1378	784
						2		110
						2.5		1471
						3.15		1961
						4	350	2941
	Multi wire with posts	2.4	3.5–10.0	4 wires	HT	1.6	413–1378	784
						2		110
						2.5		1471
						3.15		1961
						4	350	2941
Cows	Wire with battens	1.05–1.20	4.0–5.0	8–9 wires	Steel HT	2.5	413–1378	1471
						3.15		1961
					Mild	4	350	2451
	wire with posts	1.05–1.20	5.0–7.0	2–4 wires	Steel HT	2.5	413–1378	1471
Alpaca	Wire with battens	1.05–1.20	4.0–5.0	7–9 wires	Steel HT	2.5	413–1378	1471
						3.15		1961
					Mild	4	350	2451
	wire with posts	1.05–1.20	5	2–4 wires	Steel HT	2.5	413–1378	1471

counter the NIMBYism that prevents PV systems from being installed (Pascaris et al., 2022).

Although agrivoltaic systems provide higher land productivity, in general, agrivoltaics do not reduce the capital cost of a PV farm and in some cases (i.e. with expensive high racks for farm equipment to go underneath or to shade cattle) agrivoltaics can increase capital costs. For example, the agrovoltaics systems have a CAPEX approximately 50 % higher than conventional ground- mounted PV systems (Agostini, et al., 2021). Recent studies have been investigating different methods to reduce the cost of racking for agrivoltaics. The proposed approaches include the investigation of new material such as wood to reduce the cost. The studied racks include fixed-tilt wooden racking (Vandewetering et al., 2022a), seasonal tilt wooden racking (Vandewetering et al., 2022b), and vertical swinging wood racking (Vandewetering et al., 2023). The assembly of these racks, however, requires some construction knowledge. On the other hand, another study has shown the utility of microinverters in short fencing applications (Hayibo and Pearce, 2022). To overcome the cost and construction knowledge challenges, and take advantage of microinverter technology that are easy to install, this study investigates the potential for retrofitting existing animal

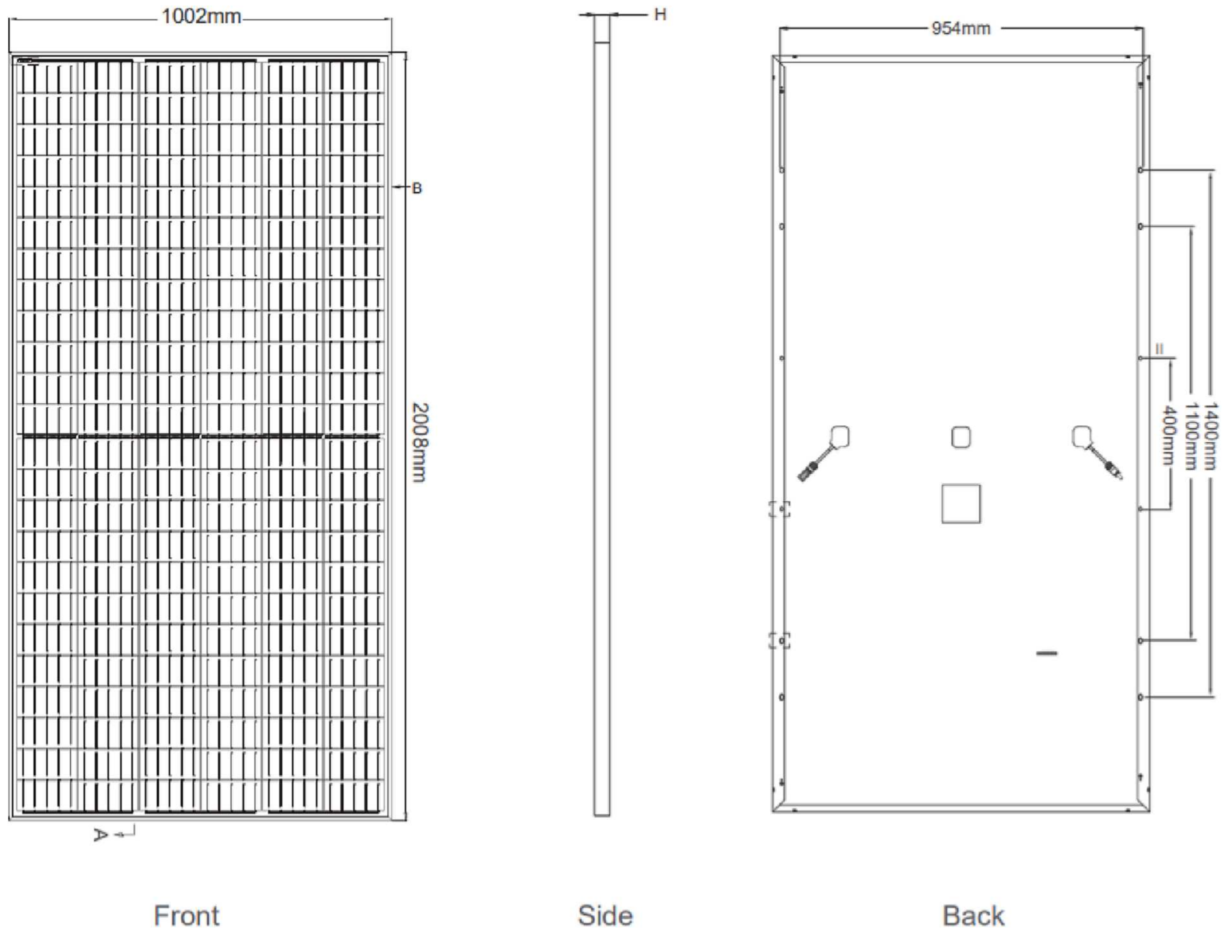


Fig. 2. JinkoSolar's Cheetah HC 72 M Mono perc Half-cell module's dimensions.

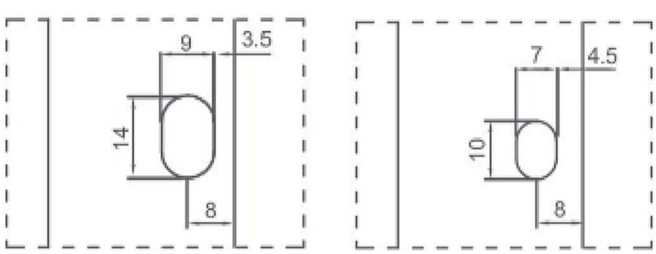


Fig. 3. Cheetah HC 72 M Mono perc module's installation slot dimensions (JinkoSolar, 2021).

Fig. 4. Stainless steel zip ties (ABSupus, 2021).

fencing on farms to have dual use for PV racking. This is complicated because common farm fence designs include both straight wires and several types of meshed fabric fences with a wide range of sizes and dimensions suitable to their application and geo-climatic conditions. For example, while farm fences for smaller animals like pigs and sheep have short and meshed fences, larger animals like horses and cows have taller and straight wired fences. Fences can be classified under Risk Category I building because they represent a low hazard to human life in the event of failure, and an agrivoltaics fence array can be viewed as agricultural facilities. Thus, in this study the types of fences are catalogued and then the wind load calculations classified under Risk Category I are run through the novel provided python-based Open Source Wind Load Calculator to determine the viability throughout the U.S. and then mapped. The base shear force for all the fences is calculated for a range of wind loads from 80 mph to 150 mph (129 km/h to 241 km/h) and the results are mapped to indicate the number of PV modules between the

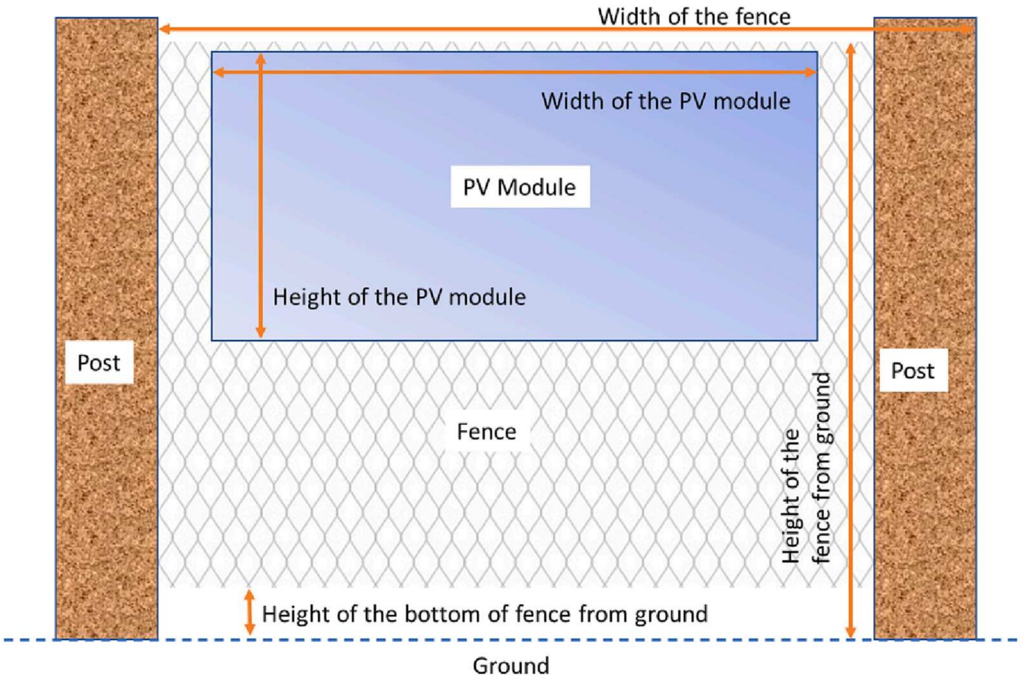


Fig. 5. Parametric nomenclature of the fence dimensions for python code.

Table 2
Description of use inputs required for the calculation of wind loads using the calculator.

User Input	Description	Representation in Fig. 5	Example Values
Fence_Top_ft	Height of top the fence from ground in feet (ft)	Height of the fence from ground	3.5
Fence_Bottom_ft	Height of the bottom of fence from ground (ft)	Height of the bottom of fence from ground	0
Fence_Seg_Width_ft	Width of the fence between two posts (ft)	Width of the fence	8
Fence_Seg_Cnt	Number of segments in the fencing,	–	6
PV_Panel_Height_ft	Height of the PV module (ft)	Height of the PV module	3
PV_Panel_Width_ft	Width of the PV module (ft)	Width of the PV module	4
Loc_Vel_mph	Local Wind Velocity in the region (m/s)	–	54
Loc_Elev_ft	Elevation of the fence location above sea level (ft)	–	250
Loc_Exp_Category	Exposure index, which is 1 for exposure category B, 2 for exposure category C and 3 for exposure category D, The Exposure category C is used for open terrain with scattered obstructions having relatively small heights (e.g. generally < 9.1 m) This category best describes the general vicinity of an agricultural fencing, particularly of pastures.	–	'B'

Table 3
System Advisor Model simulation parameters.

Parameters	Value	Source
System Type	Detailed PV Res. Model	This Study
PV Module	Trina Solar TSM-230PD05	(Freeman et al., 2018)
Efficiency	14.22 %	
Length	1.618 m	
Width	0.985 m	
Module Type	Multi-Crystalline Silicon - Monofacial	
Number of Modules	15	This Study
Inverter	SunPower: SPR-3300f [240 V]	(Freeman et al., 2018)
Tilt Angle	90 degrees	This Study
Azimuth	Variable	
DC Power Rating	3.451 Wdc	
DC to AC Ratio	1.10	
Soiling Losses	0 %	
Module Cost	0.61 USD/W	(Freeman et al., 2018)
Inverter Cost	0.28 USD/W	
Zip-Tie Cost	7.8 USD/module	(Amazon.com: 2021)
System Lifetime	25 years	This Study

vertical fence poles a fence can tolerate in a specific location. The results are discussed in the context of the potential for farmers to install low-cost agrivoltaic systems.

2. Methods

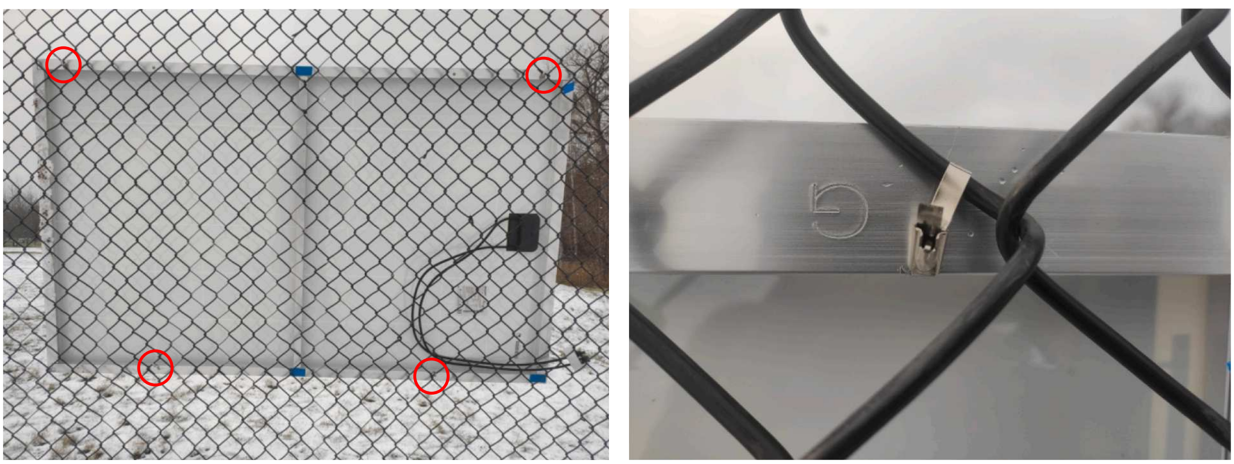
2.1. Fence and fence mesh types

Fence design and type are dependent on the type of animal, topography, soil, availability of materials, local laws and budget, but three types of farm fences are most common (Conventional Farm, 2022) (conventional farm fencing):

1. Multiwire, multi batten: In this type, as shown in Fig. 1a, there are multiple battens placed between the main posts to support the fence

(a) (b)

Fig. 6. Front of modules installed on chain link fence during field mounting and unmounting test. (a) Group of three modules. (b) Close-up of a single module installed between two posts.



(a) (b)

Fig. 7. Back of modules installed on chain link fence during field mounting and unmounting test. (a) Back of a module with red circles indicating the position of zip-ties (b) Close-up of a single zip-tie attached to the chain link fence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

wire. There are some variations of this design with most common ones are tabulated in Table 1.

2. Post and wire (without battens): In this type, as shown in Fig. 1b, there are many numbers of posts on to which the fence wires or mesh are attached. Some of the most common farm fences of this type are listed in Table 1.
3. Netting /Mesh fences: These types of fences have prefabricated meshes of various designs suitable to the need and sometimes aesthetics, as shown in Fig. 1c and Fig. 1d. Some of these meshes need battens to be constructed and some of them have battens prefabricated or inbuilt with them. These are used mainly for containment purposes like pig fence, deer fence etc.

2.2. Material properties

Normally for fences, high tensile steel wires and mild steel wire are predominantly used (Minisistry of ag[4]). Their diametric dimensions are generally 4 mm, 3.15 mm and 2.5 mm for high tensile (HT) wire and mild steel wires (Gregory, 2019). Generally, 4 mm diameter mild steel can be replaced with a smaller diameter HT wire. The tensile strength wire for these wires is listed in Table 1. The posts for the fences are made of concrete, metal, or wood.

2.3. Solar PV modules

The JinkoSolar Cheetah HC 72 M monocrystalline silicon passivated emitter and rear contact (PERC) half-cell modules were selected as a representative silicon-based PV modules (JinkoSolar, 2021) (Fig. 2). It is a monofacial PV module with 390–410 Watt per module, a mass of 216 N with and area of 2 m by 1 m.

2.4. Fasteners

Stainless steel cable ties were selected for fastening the PV modules to the fences because of their ease of use and high tensile strength. Although they come in various length and widths, anything less than with a width of 7 mm or smaller can fit all slots of the selected module as shown in Fig. 3. The material of the zip ties, as shown in Fig. 4, are usually stainless-steel type 304 or type 316 which usually have a capacity of 890 to 1557 N for a width of 4.75 mm to 7.9 mm.

2.5. Wind load calculations

Wind pressure that the existing post size can withstand is a prominent limiting factor of the wind load capacity of the fence with addition

Shear force (N) for Goat/Sheep fence with battens											
Wind speed (mph)	80	85	90	95	100	105	110	120	130	140	150
No. of panels											
1	871.8885	984.2955	1103.467	1229.491	1362.323	1501.964	1648.414	1961.738	2302.341	2670.178	3065.249
2	2220.55	2506.774	2810.398	3131.332	3469.621	3825.22	4198.219	4996.238	5863.632	6800.401	7806.591

Shear force (N) for Goat/Sheep fence with posts											
Wind speed (mph)	80	85	90	95	100	105	110	120	130	140	150
No. of panels											
1	727.1745	820.936	920.349	1025.458	1136.219	1252.675	1374.828	1636.176	1920.22	2227.003	2556.481
2	1700.835	1920.086	2152.599	2398.417	2657.54	2929.925	3215.615	3826.867	4491.252	5208.77	5979.465
3	2915.996	3291.888	3690.563	4112.023	4556.266	5023.294	5513.105	6561.036	7700.102	8930.305	10251.6
4	4331.719	4890.105	5482.311	6108.382	6768.317	7462.027	8189.647	9746.346	11438.41	13265.85	15228.66

Index	
Colour	Suitable wire diameter
	2.5mm steel HT, 3.15 mm steel HT and 4 mm mild steel
	3.15 mm steel HT and 4 mm mild steel
	4 mm mild steel
	none

Fig. 8. Shear force (N) matrix for Goat/Sheep fence types.

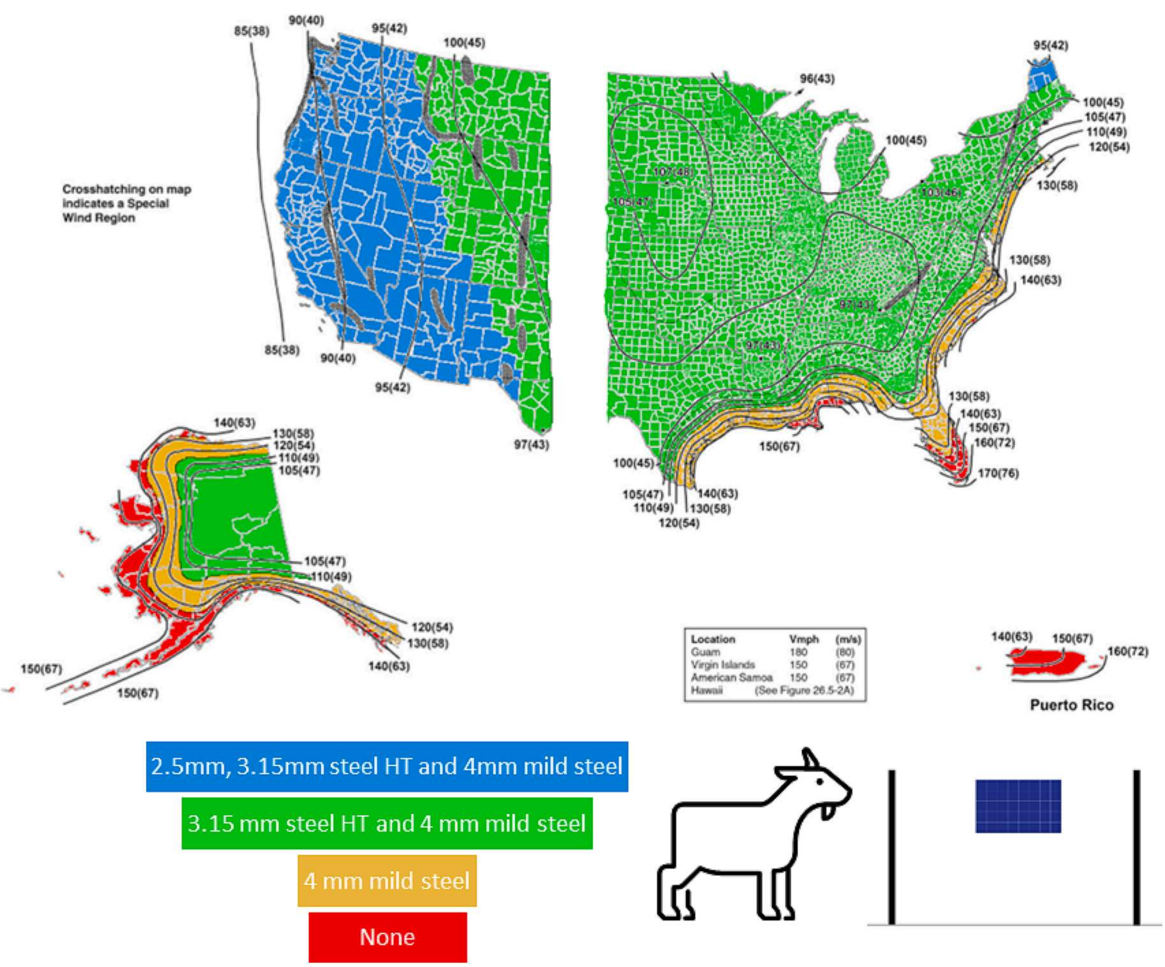


Fig. 9. Wire specifications map for Goat/Sheep farm fence with battens for one solar module in USA at Category C wind exposure.

of the PV. The wind load calculations are done to understand if a fence can withstand the topological, geographical and climatic challenges of wind pressure at their respective regions with the addition of PV. For this, the line posts size and spacing play a major role along with the mesh fabric (CLFMI, 2014). The other factors that influence the size and spacing of posts are height of fence, footing depth, style and size of mesh

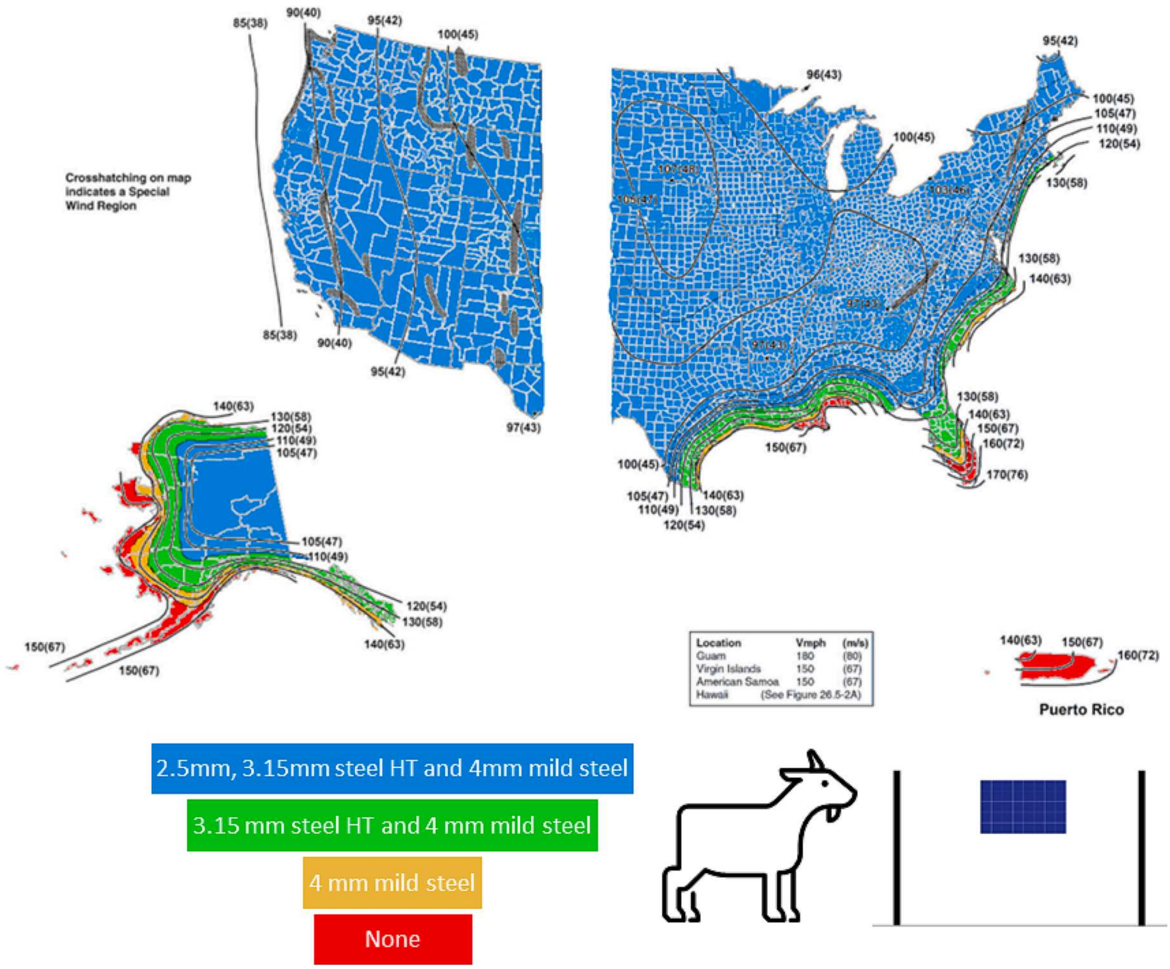


Fig. 10. Wire specifications map for Goat/Sheep farm fence with posts for one solar module in USA at Category C wind exposure.

fabric, material strength of post, soil type and windspeed. A minimum of 0.61 m of footing depth must be maintained for all common fences of 1.22 m height (CLFMI, 2014). For every foot increase in fence height, 0.002 m of footing depth should also be increased.

To calculate the wind loads on a farm fence which is considered as a freely standing walls or solid signs and the wind load calculations depend mainly on the following basic parameters according to both Main Wind Force Resisting System (MWFRS) and Components & Cladding (C&C) (ASCE, 2017).

- Risk category
- Basic wind speed, V
- Wind directionality factor, K_d
- Exposure,
- Topographic factor, K_{zt},
- Ground elevation factor, K_e,
- Velocity pressure exposure coefficient, K_z
- Gust-effect factor
- Force coefficient C_f
- Gross area of the solid free-standing wall

The first step in determining wind loads is to identify the risk category and basic wind speed for the fences. Since the farm fences represent low risk to human life in the event of failure, they can be classified under Risk Category I. Then the basic wind speed for Risk Category I is considered 38 m/s to 76 m/s, the next step is to identify the wind load parameters for these conditions. Fences can be considered as solid free-standing walls, therefore the wind directionality factor, K_d is 0.85. The gust-effect factor for a rigid building or other structure is permitted to be taken as 0.85 (ASCE, 2017). The remaining required parameters are inputs to the python code (OSF, 2022). These parameters are then use by the code ‘’WL_WireFence.py" which calculates the wind load for the given input parameters, and returns the base moment and base shear force values for a given input values of the fence and solar module dimension specified.

2.5.1. Open Source wind load calculator

The Open Source Wind Load Calculator is provided in python code (OSF, 2022) that can calculate the wind load on a fence in any region when the required parameters are known. The required input parameters for calculating wind load include the basic wind speed at the installation site, exposure category, elevation of the fence above sea level, height of the top of the fence post from the ground in feet, diameter of the fence post in feet, height of the top the fence from the ground in feet, height of the bottom of the fence from the ground in feet, width of the fence between two posts, number of such segments in the fencing, fence solidity ratio, epsilon (see Appendix A1), height of the PV module, width of the PV module. With these inputs, the base moment and the base shear force are calculated using the calculator.

The calculator is designed primarily for locations in the United States. Therefore, the units of the inputs and results in this code are US units. However, this code can also be used by converting the US units to SI Units for measuring the wind load in other parts of the world with the addition of an appropriate basic wind speeds (e.g. 3 *sec* gust) for the desired return interval (e.g. 50, 100) years. The following example with the help of Fig. 5 and the python code "WL_WireFence.py" provided in

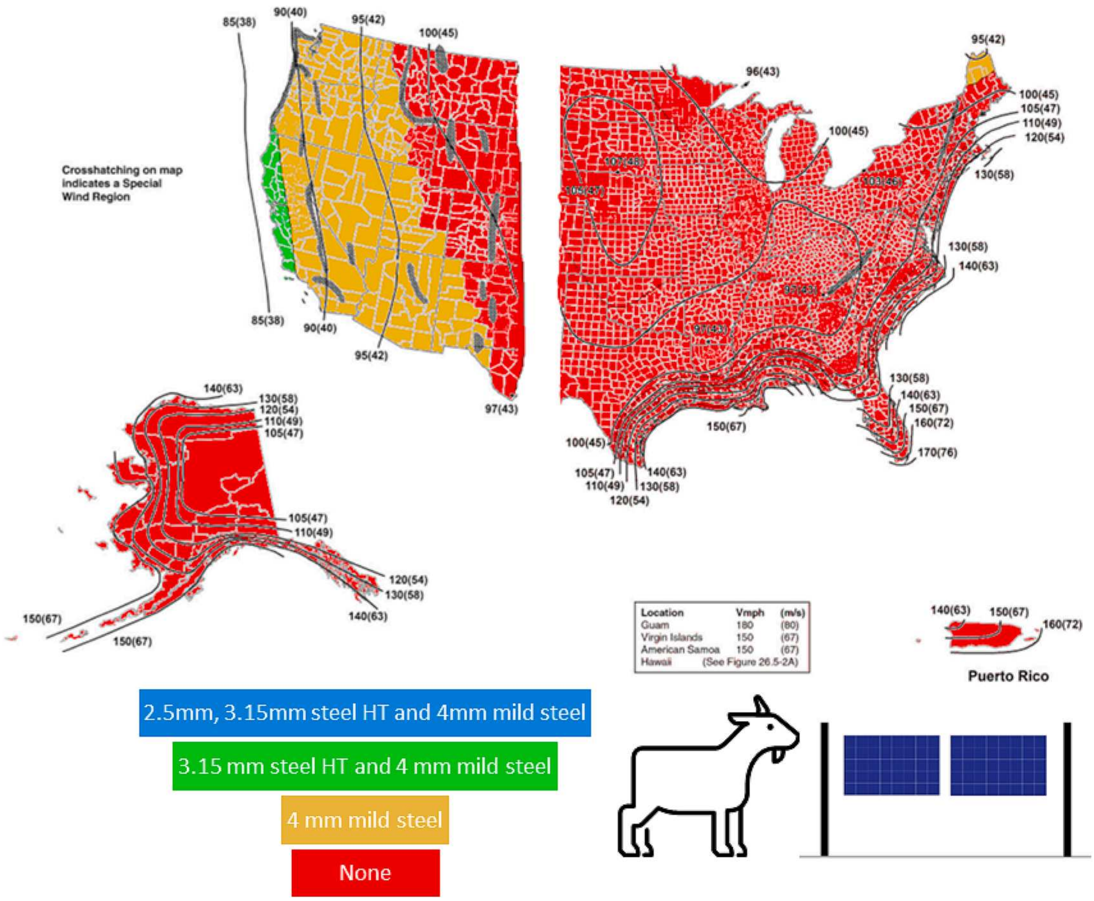


Fig. 11. Wire specifications map for Goat/Sheep farm fence with posts for two solar modules in USA at Category C wind exposure.

Shear force (N) for Pig fence with Posts											
Wind speed (mph)	80	85	90	95	100	105	110	120	130	140	150
No. of panels											
1	921.506	1040.321	1166.301	1299.489	1439.842	1587.449	1742.22	2073.389	2433.349	2822.146	3239.689
2	3241.87	3659.769	2754.773	4103.034	5065.435	6129.208	4115.182	7294.262	8560.599	9928.262	11397.25

Index	
colour	Suitable wire diameter
	2mm, 2.5mm, 3.15 mm and 4 mm steel HT
	2.5mm, 3.15 mm and 4 mm steel HT
	3.15 mm and 4 mm steel HT
	4 mm steel HT
	none

Fig. 12. Shear force (N) matrix for Pig Farm fence types.

Appendix A2, explains how various inputs are taken for calculating the wind load.

2.5.2. *Example calculation*

Fig. 5 depicts the user inputs (Appendix A2) that are required for calculating the wind loads automatically by this calculator as coded in the “WL_WireFence.py”. The user inputs are shown in Table 2.

The program outputs the wind loads in terms of the base shear force in pound force (lbf) and base moment in feet pound force (ft- lbf). For the example, the base shear force is 204.76 lbf (910.82 N) and the base moment is 376.25 ft-lbf (510.13 *N*-m).

2.5.3. *Simulations*

Here, to determine the viability of using fences for PV racks, the base shear force for all the fences from Table 1 have been calculated for a range of wind loads from 80 mph to 150 mph (129 km/h to 241 km/h) and compared with the recommended tension respectively. Upon that comparison, a matrix of results has been created to show the wind load feasibility of number of solar modules to be fixed on each fence type. For this matrix, the local wind exposure is considered as category C.

Finally, the output ratio or energy yield of the vertically mounted solar PV system on a goat/sheep farm was compared to the optimal tilt angle south facing PV for the geographic center of the U.S. (about 20 mi (32 km) north of Belle Fourche, South Dakota) The energy yield is

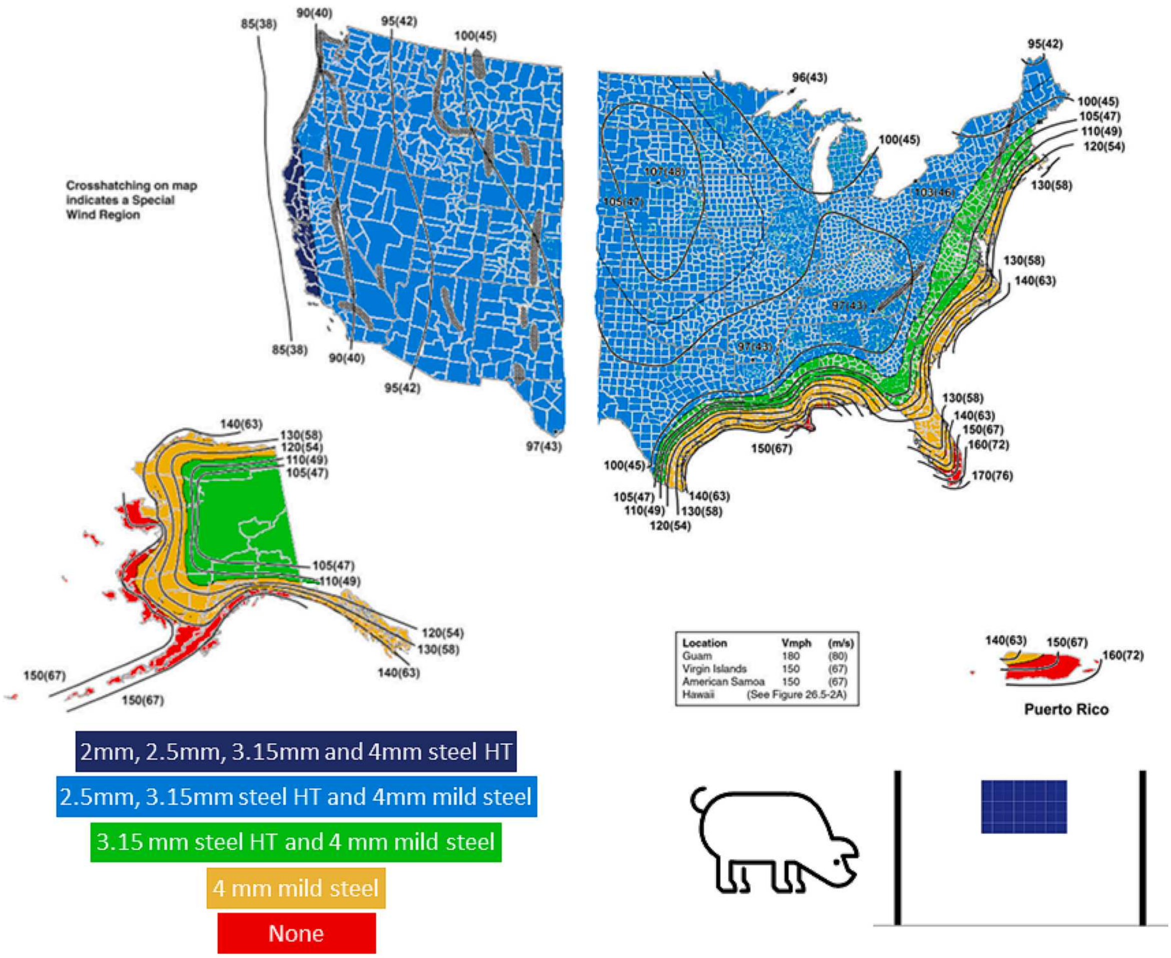


Fig. 13. Wire specifications map for Pig farm fence with posts for one solar module in USA at Category C wind exposure.

Shear force (N) for Cow fence with battens

Wind speed (mph)	80	85	90	95	100	105	110	120	130	140	150
No. of panels											
1	871.8885	984.2955	1103.467	1229.491	1362.323	1501.964	1648.414	1961.738	2302.341	2670.178	3065.249
2	2220.55	2506.774	2810.398	3131.332	3469.621	3825.22	4198.219	4996.238	5863.632	6800.401	7806.591

Shear force (N) for Cow fence with Posts

Wind speed (mph)	80	85	90	95	100	105	110	120	130	140	150
No. of panels											
1	792.5005	894.6725	1003.03	1117.573	1238.302	1365.216	1498.315	1783.115	2092.702	2427.03	2786.145
2	1946.831	2197.766	2463.965	2745.339	3041.931	3353.698	3680.729	4380.358	5140.863	5962.155	6844.323

Index

Colour	Suitable wire diameter
	2.5mm steel HT
	2.5mm steel HT, 3.15 mm steel HT and 4 mm mild steel
	3.15 mm steel HT and 4 mm mild steel
	4 mm mild steel
	none

Fig. 14. Shear force (N) matrix for Cow Farm fence types.

obtained by dividing the lifetime energy production of the PV system by the nameplate DC power. The simulation was performed using the open-source System Advisor Model (SAM) developed by the National Renewable energy Laboratory (NREL) (Model, 2021) for a range of orientations covering 360 degrees. SAM is open source and available for free download (Model, 2021; System Advisor Model, 2021). The algorithm used for the SAM simulation is developed in a recent study that compared the economic performance of string inverters and micro-inverters for small-scale vertical fencing applications (Hayibo and Pearce, 2022). The number of modules used for the simulation is 15

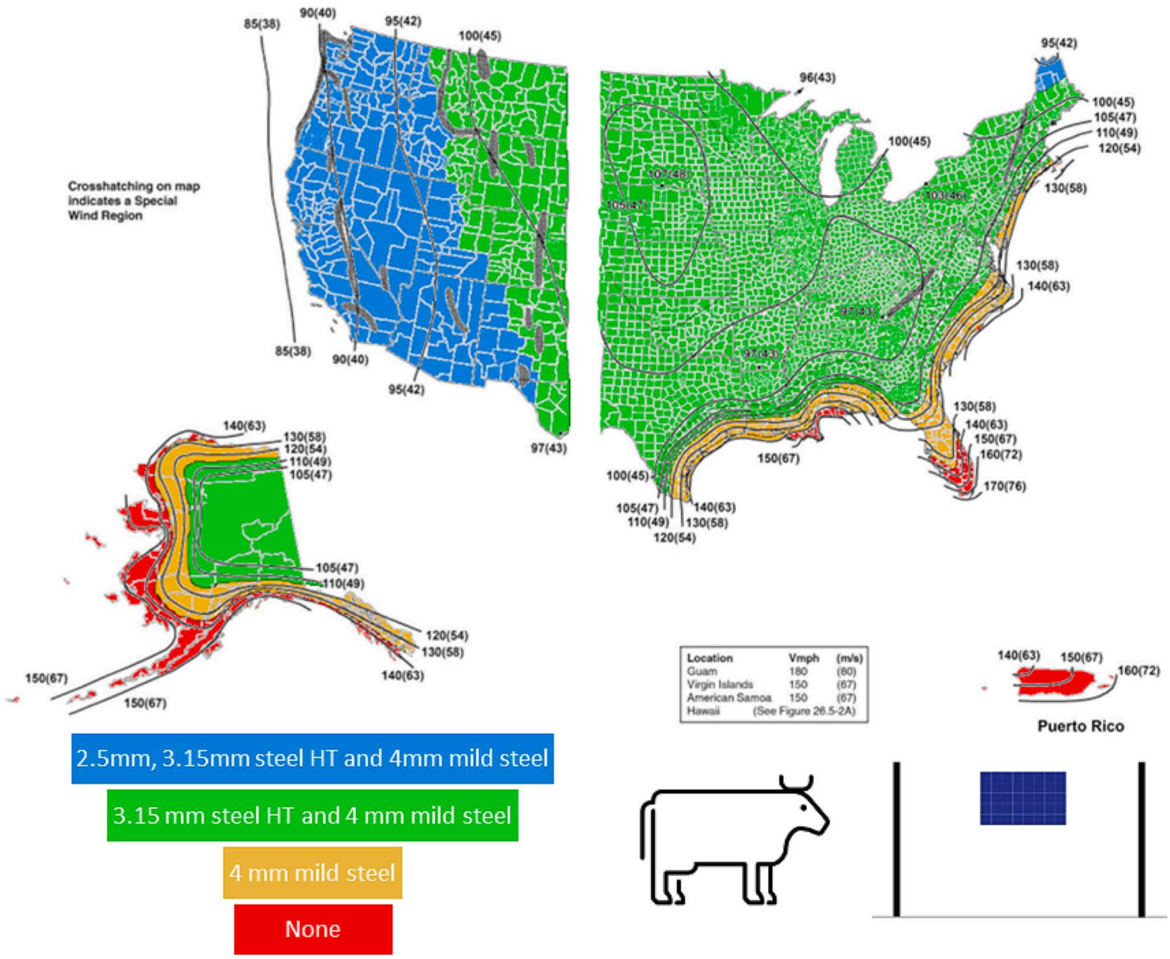


Fig. 15. Wire specifications map for Cow farm fence with battens for one solar module in USA at Category C wind exposure.

modules and a string inverter was used to optimize the energy generation. The levelized cost of electricity (LCOE) was calculated by dividing the cost of the system by the lifetime energy generated by the PV. The cost used in this study include the module cost, the inverter cost, the wire cost, and the wire duct cost. The LCOE, therefore, relates to the modules, the inverter, the wire, and the wire duct, which are the most important part of the proposed system. Ancillary costs of a PV system installation were not considered in this study. Table 3 shows the parameters used in the SAM simulation.

3. Results

A field test was conducted where three modules were mounted and unmounted on an existing chain link fence as shown in Fig. 6. The installation of the modules on the fence was an easy and quick process. The operation was easily performed with two people. The mounting of a single module required a total of 4 zip-ties as displayed on Fig. 7a and was completed under 7 min amid a snowy, windy, and cold day. The zip-ties held the modules tight to the fence links as displayed on Fig. 7b. Unmounting the modules required less time than the mounting operation. For each module, the unmounting process was completed under two minutes, since it only required cutting down and removing the four zip-ties holding the modules to the fence links.

3.1. Goat/ sheep farm

For a goat or sheep farm two fence types, with battens and with posts are considered. For the fence type with battens, the fence height is 1.2 m and segment width is 5 m; approximately-two solar panels can be attached in the space available in each segment. While the fence type with posts has a fence height of 1.2 m and segment width of 10 m, approximately-four solar modules can be attached for the space available. Simulations were run and an output matrix is provided (Fig. 8) with colors denoting the feasibility of each number of panels to be fixed with respective to the fence wire specification and wind load. Blue indicates a 2.5 mm steel HT or 3.15 mm steel HT or 4 mm mild steel fencing material would work, green indicates only 3.15 mm steel HT or 4 mm mild steel fencing material would work, yellow only the 4 mm mild steel and red denotes the fence cannot be used for PV racking. As wind speeds vary geographically the results are mapped for the continental U.S.

From Fig. 8, it can be seen the fence type with battens can withstand one solar panel on each segment up to 130 mph (209 km/hkm/h) of wind loads with varying wire specifications. After 130 mph (209 km/h), the fence with battens cannot withstand any modules on it. Similarly, the fence type with battens can withstand one solar module on it with a wire specification of 2.5 mm steel HT, 3.15 mm steel HT and 4 mm mild steel from 80 to 95 mph (129 to 153 km/h) wind loads; 3.15 mm steel HT and 4 mm mild steel from 100 to 110 mph (161 to 177 kpm) wind load; 4 mm mild steel from 120 to 130 mph (193 to 209 km/h); and neither of the wire specification above 140 mph of wind loads. Similarly, two solar modules can be fixed on each segment of the fence type with battens only wires with 4 mm mild steel can withstand it at 80 mph (129 km/h) wind loads. Above 80 mph (129 kmh) wind load is not suitable for two solar modules to be fixed on the fence with any type of wire specifications.

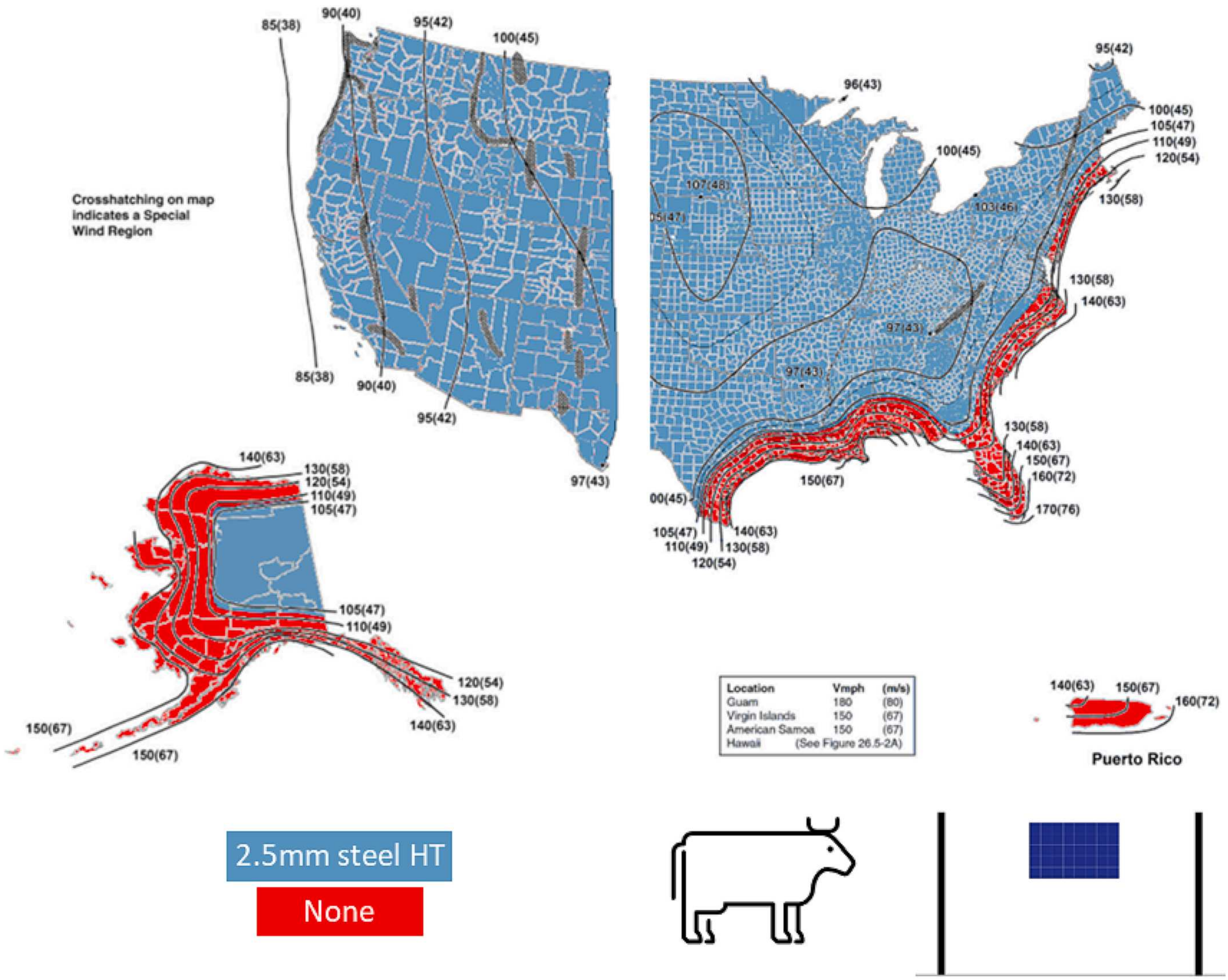


Fig. 16. Wire specifications map for Cow farm fence with posts for 1 solar module in USA at Category C wind exposure.

Shear force (N) for Alpaca fence with battens											
Wind speed (mph)	80	85	90	95	100	105	110	120	130	140	150
No. of panels											
1	871.8885	984.2955	1103.467	1229.491	1362.323	1501.964	1648.414	1961.738	2302.341	2670.178	3065.249
2	2220.55	2506.774	2810.398	3131.332	3469.621	3825.22	4198.219	4996.238	5863.632	6800.401	7806.591
Shear force (N) for Alpaca fence with posts											
Wind speed (mph)	80	85	90	95	100	105	110	120	130	140	150
No. of panels											
1	871.8885	984.2955	1103.467	1229.491	1362.323	1501.964	1648.414	1961.738	2302.341	2670.178	3065.249
2	2220.55	2506.774	2810.398	3131.332	3469.621	3825.22	4198.219	4996.238	5863.632	6800.401	7806.591

Index	
colour	Suitable wire diameter
(light blue)	2.5mm steel HT
(blue)	2.5mm steel HT, 3.15 mm steel HT and 4 mm mild steel
(green)	3.15 mm steel HT and 4 mm mild steel
(orange)	4 mm mild steel
(red)	none

Fig. 17. Shear force (N) matrix for Alpaca Farm fence types.

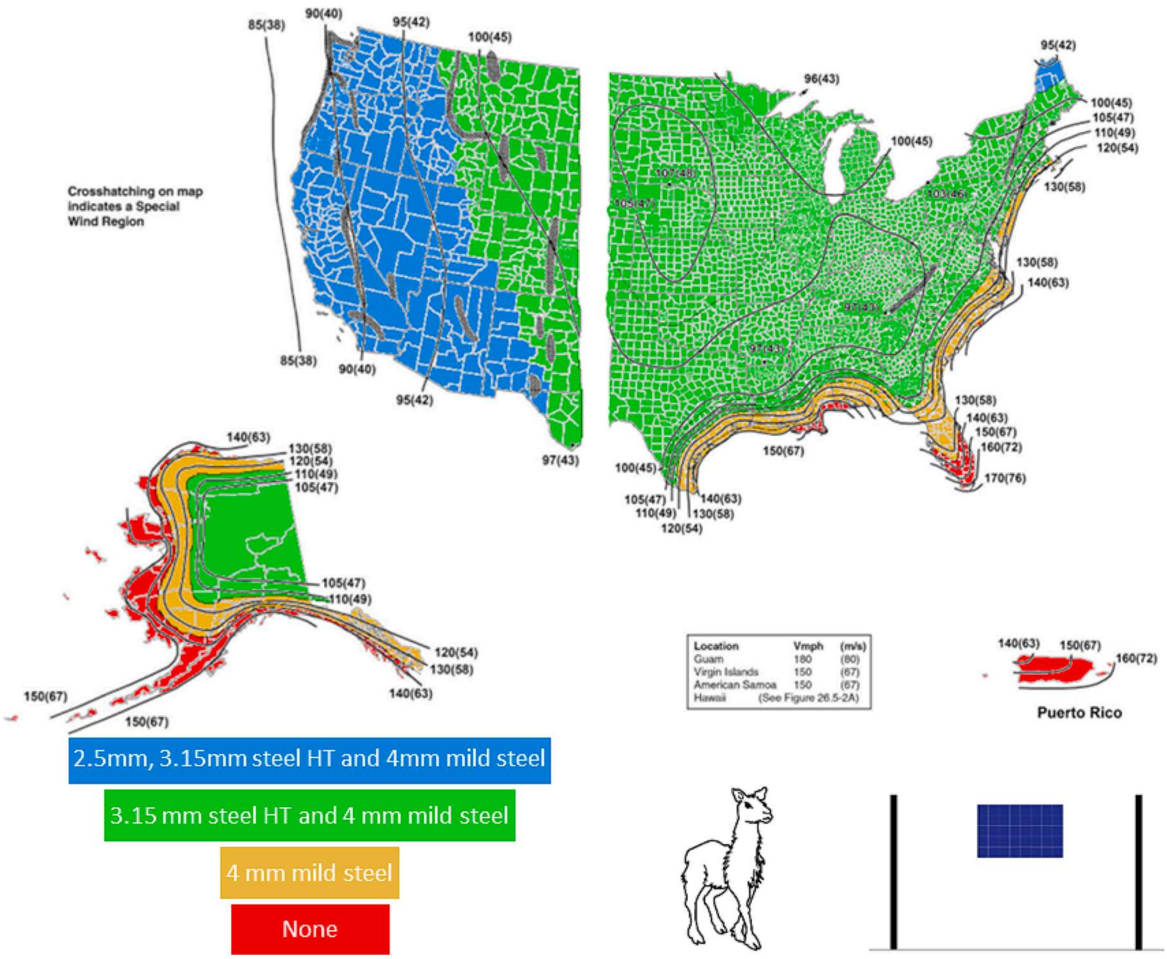


Fig. 18. Wire specifications map for Alpaca farm fence with battens for one solar modules in USA at Category C wind exposure.

According to the matrix in Fig. 8, for goat and sheep farm type fences with battens, the following maps are drawn for the wind loads in Category C in USA, for one solar module in Fig. 9 and two solar modules is not appropriate. For the maps all the windspeeds shown for category C and the color coding is for fence wire specifications.

Similarly, for goat/sheep farm type fence with post, the following graphs could be drawn for the wind loads in Category C in USA, for 1 solar module in Fig. 10, for 2 solar modules in Fig. 11. Three or more solar modules is not appropriate for this type of fence.

3.2. Pig farms

For this pig farm type, only one fence type with posts is considered for comparison. The height of the other mesh type fence is smaller than that of the solar module, so solar modules may not be properly fixed on this type of fence. For the fence type with posts, the fence height is 2.4 m and segment width is taken as 5 m. Therefore, approximately solar panels can be fixed in the space available in each segment. Accordingly, the following matrix has been drawn with color coding the feasibility of each number of panels to be fixed to the fence with the feasible wire specification and wind load.

From Fig. 12, the fence type with posts can withstand one solar panel on each segment up to 140 mph (225 km/h) of wind loads with varying wire specifications as color coded in the index. After 140 mph (225 km/h), the fence with battens cannot withstand any modules on it. To detail the results, the fence type with posts can withstand 1 solar module on it with a wire specification of 2 mm steel HT, 2.5 mm steel HT, 3.15 mm steel HT and 4 mm mild steel from 80 to 85 mph (129 to 137 km/h) wind loads; 2.5 mm steel HT, 3.15 mm steel HT and 4 mm mild steel from 90 to 100 mph (145 to 161 km/h) wind loads; 3.15 mm steel HT and 4 mm mild steel from 105 to 110 mph (169 to177 km/h) wind load; 4 mm mild steel from 120 to 140 mph (193to 225 km/h); and neither of the wire specification above 150 mph (241 km/h) of wind loads. Similarly, it can be seen that two solar modules cannot be fixed on each segment of this fence type with any type of wire specifications. According to the above the matrix in Fig. 12, for pig farm type fence with posts, the following maps of wind loads in Category C in USA, for 1 solar module in Fig. 13. Two solar modules and above are not appropriate for this type of fence.

3.3. Cow farms

For cow farms there are two fence types, with battens and with posts are considered. For the fence type with battens, the fence height is 1.2 m and segment width is 5 m. Therefore, approximately-two solar modules can be fixed in the space available in each segment. While the fence type with posts has a fence height of 1.2 m and segment width of 7 m, approximately-three solar modules can be fixed for the space available. The PV-racking viability matrix is shown in Fig. 14 with respective to the fence wire specifications and wind loads.

From Fig. 14, it can be seen that the fence type with battens can withstand 1 solar module on each segment up to 130 mph (209 km/h) of wind loads with varying wire specifications as color coded in the index. After 130 mph (209 km/h), the fence with battens cannot withstand any modules on it. Specifically, the fence type with battens can withstand one solar module on it with a wire specification of 2.5 mm steel HT, 3.15 mm steel HT and 4.0 mm mild steel from 80 to 95 mph (129 to 153 km/

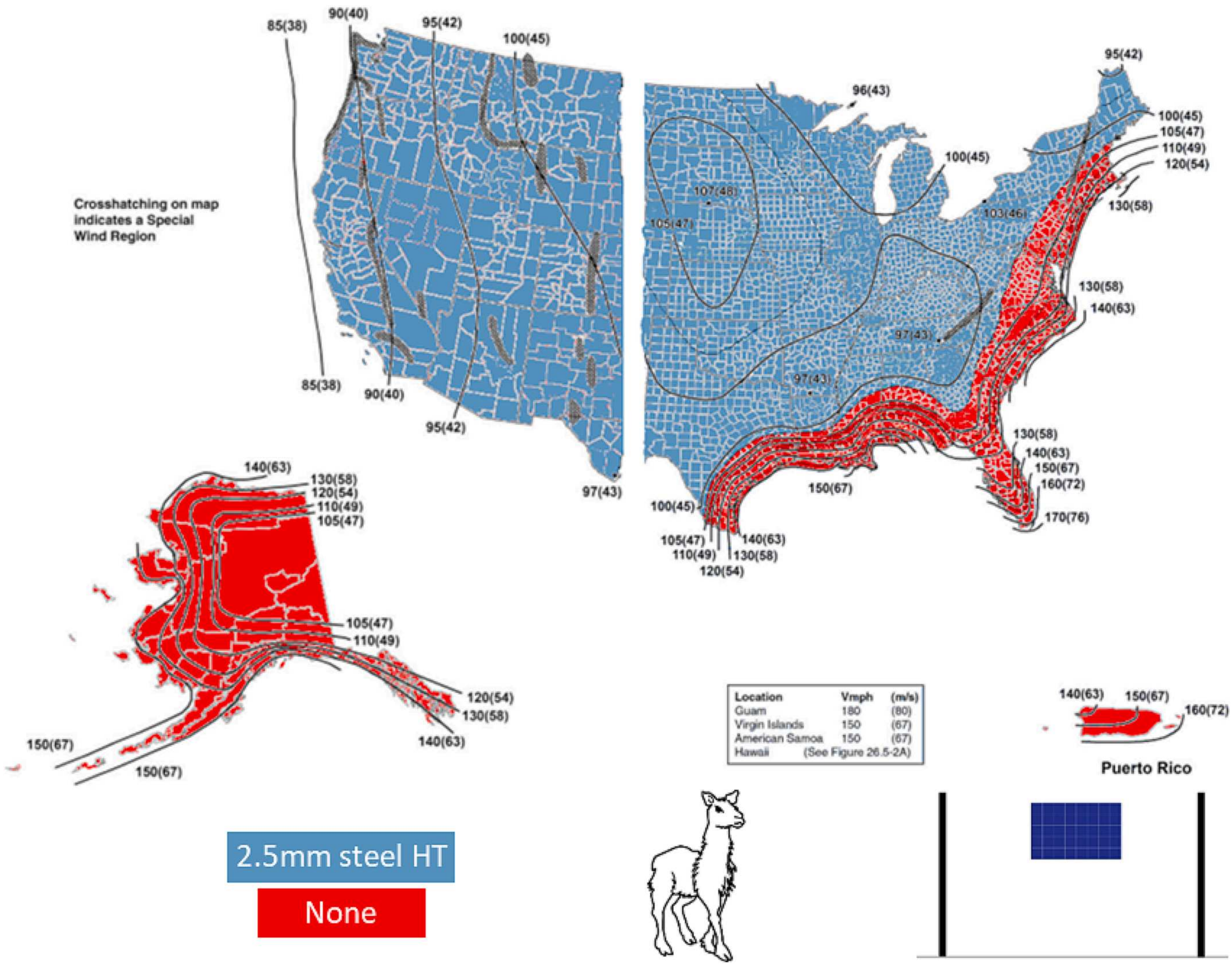


Fig. 19. Wire specifications map for Alpaca farm fence with posts for one solar module in USA at Category C wind exposure.

h) wind loads; 3.15 mm steel HT and 4 mm mild steel from 100 to 110 mph (161 to 177 km/h) wind load; 4 mm mild steel from 120 to 130 mph (193 to 209 km/h); and neither of the wire specification above 140 mph of wind loads. Similarly, two solar modules can be fixed on each segment of the fence type with battens only wires with 4 mm mild steel can withstand it at 80 mph (129 km/h) wind loads. Above 80 mph (129 km/h) wind load is not suitable for two solar modules to be fixed on the fence with any type of wire specifications. According to the above the matrix in Fig. 14, for Cow farm type fence with battens, the following maps for the wind loads in Category C in USA, for 1 solar module in Fig. 15.

Similarly, for cow farm type fence with posts, the following maps are shown for the wind loads in Category C in USA, for one solar module in Fig. 16.

3.4. Alpaca farms

For alpaca farms two fence types, with battens and with posts are considered. For both the fence types, with battens and posts, the fence height is 1.2 m and segment width is 5 m. Therefore, approximately-two solar panels can be fixed in the space available in each segment. The results are illustrated in Fig. 17 for the feasibility of each number of PV modules to be fixed with respective to the fence wire specification and wind load.

From Fig. 17, it is clear that the alpaca fence with battens can withstand one solar panel on each segment up to 130 mph (209 km/h) of wind loads with varying wire specifications as color coded in the index. After 130 mph (209 km/h), the fence with battens cannot withstand any modules on it. The fence type with battens can withstand one solar module on it with a wire specification of 2.5 mm steel HT, 3.15 mm steel HT and 4 mm mild steel from 80 to 95 mph (129 to 153 km/h) wind loads; 3.15 mm steel HT and 4 mm mild steel from 100 to 110 mph (161 to 177 km/h) wind load; 4 mm mild steel from 120 to 130 mph (193 to 209 km/h); and neither of the wire specification above 140 mph (225 km/h) of wind loads. Similarly, two solar modules can be fixed on each segment of the fence type with battens only wires with 4 mm mild steel can withstand it at 80 mph wind loads. Above 80 mph (129 km/h) wind load is not suitable for two solar modules with any type of wire specifications. According to the above the matrix in Fig. 17, for alpaca farm type fence with battens, the following graphs could be drawn for the wind loads in Category C in USA, for one solar module in Fig. 18.

Similarly, for Alpaca farm type fence with posts, the following graphs could be drawn for the wind loads in Category C in USA, for 1 solar module in Fig. 19.

Fig. 20 shows a summary of the shear force matrix for all the types of fences described in this study.

Finally, the output ratio of the vertical mounted solar PV system was compared to the optimal tilt angle south facing PV for the geographic

Fence Types		Fence With Battens (sheep, cow, alpaca)		Sheep Fence with Posts				Pig fence with Posts		Cow Fence with Posts		Alpaca fence with Posts	
N° of modules		1	2	1	2	3	4	1	2	1	2	1	2
Wind Speed km/h	129	0.87	2.22	0.73	1.70	2.92	4.33	0.92	3.24	0.79	1.95	0.87	2.22
	137	0.98	2.51	0.82	1.92	3.29	4.89	1.04	3.66	0.89	2.20	0.98	2.51
	145	1.10	2.81	0.92	2.15	3.69	5.48	1.17	2.75	1.00	2.46	1.10	2.81
	153	1.23	3.13	1.03	2.40	4.11	6.11	1.30	4.10	1.12	2.75	1.23	3.13
	161	1.36	3.47	1.14	2.66	4.56	6.77	1.44	5.07	1.24	3.04	1.36	3.47
	169	1.50	3.83	1.25	2.93	5.02	7.46	1.59	6.13	1.37	3.35	1.50	3.83
	177	1.65	4.20	1.37	3.22	5.51	8.19	1.74	4.12	1.50	3.68	1.65	4.20
	193	1.96	5.00	1.64	3.83	6.56	9.75	2.07	7.29	1.78	4.38	1.96	5.00
	209	23.03	5.86	1.92	4.49	7.70	11.44	2.43	8.56	2.09	5.14	23.03	5.86
	225	2.67	6.80	2.23	5.21	8.93	13.27	2.82	9.93	2.43	5.96	2.67	6.80
	241	3.07	7.81	2.56	5.98	10.25	15.23	3.24	11.40	2.79	6.84	3.07	7.81

2mm, 2.5mm, 3.15mm and 4mm steel HT	2.5mm, 3.15mm steel HT and 4mm mild steel	2.5mm steel HT	3.15 mm steel HT and 4 mm mild steel	4 mm mild steel	None

Fig. 20. Shear force (kN) matrix for all types of fences analyzed in this study.

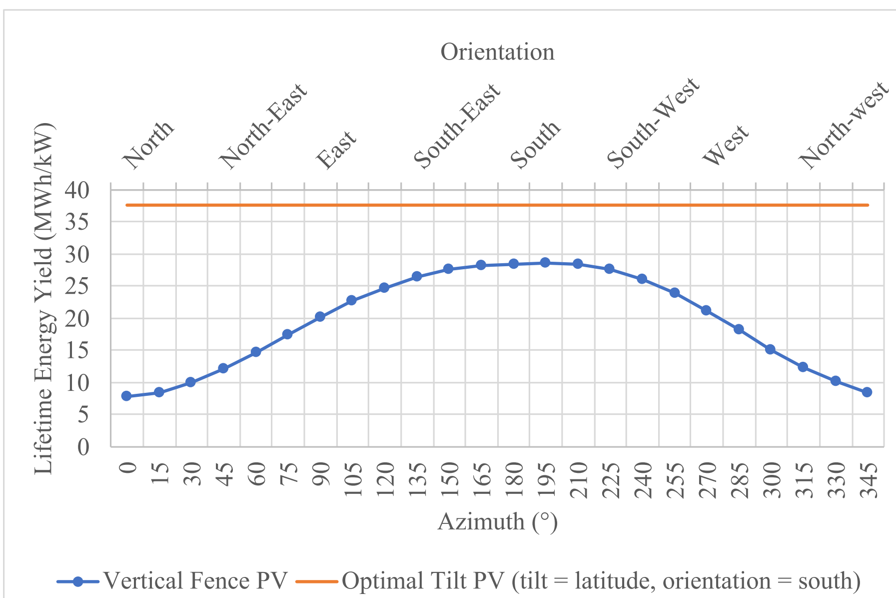


Fig. 21. Energy yield of the vertical fence PV for different orientations compared to the energy yield of an optimized PV system (tilt = latitude, orientation = south) for the geographical center of the U.S.

center of the U.S. and is shown in Fig. 21.

As can be seen on Fig. 21, the vertical fence PV has a lower energy yield when compared to an optimized ground-mounted PV system. This is explained by the higher amount of solar energy received by an optimized inclined surface as compared to a vertical surface. Nevertheless, the vertical fence PV energy yield is optimized for a south orientation yielding 29 MWh/kW. The energy yield of the optimized vertical PV represents 76 % of that of an optimized ground-mounted PV system (38 MWh/kW). Furthermore, when the system costs are estimated on the same basis as proposed by (Hayibo and Pearce, 2022) using levelized cost of electricity (LCOE), which is the average net present cost of solar electricity generation for the PV over its lifetime, the vertical PV fencing becomes cost-competitive with an optimized ground-mounted PV system. This is especially true when the orientation of the fence is between south-east and south-west. The LCOE of the optimized ground-mounted PV system is estimated at 0.038 USD/kWh while the LCOE for a vertical fencing PV oriented due South is 0.035 USD/kWh. It should be noted that the LCOE calculation here does not include administrative costs, installation costs, financing, and taxes.

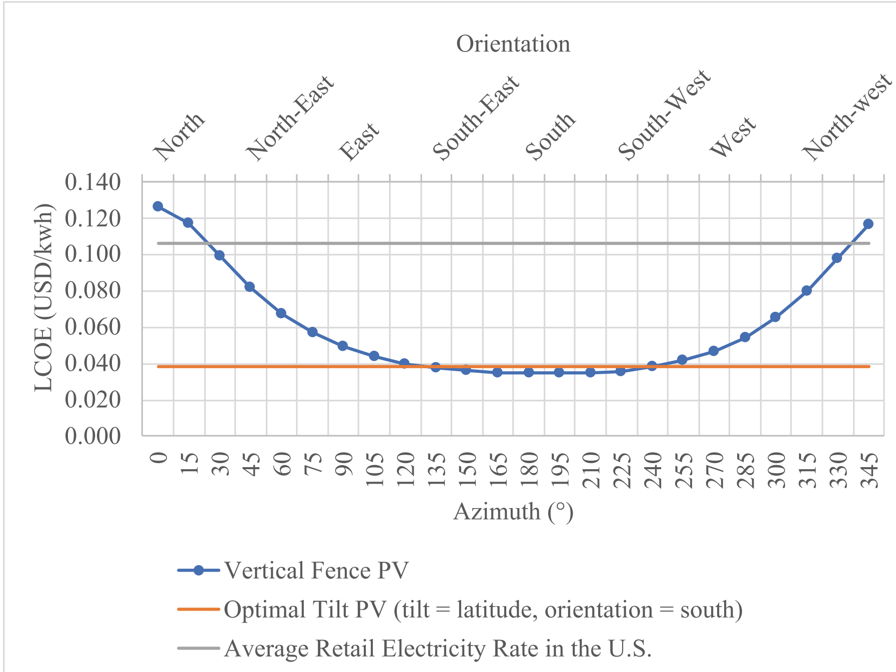


Fig. 22. Levelized cost of electricity of the vertical fence PV for different orientations compared to the levelized cost of electricity of an optimized PV system (tilt = latitude, orientation = south) for the geographical center of the U.S.

Fig. A1. Chain link fence fabric dimension measurement.

4. Discussion

4.1. Economics

It is clear from the results that having single rows of modules on farm fences is viable for a wide range of farms including sheep, goats, pigs, cows, and alpaca in the U.S. The cost of the racking retrofit is only the cost of 4 stainless steel zip ties per module (see Figs. 6 and 7), which can be purchased in 120 packs for US$11 or about 37cents per module (Amazon, 2021). If the modules range in power from 250 to 500 W then the racking cost of an existing fence is less than a penny a Watt. This appears extremely promising, but it should be noted that the length of cables that are included with a module may need to be extended for this application. This is far less expensive than all types of conventional PV racking. In conventional residential rooftop PV system, the structural balance of system (racking) represents 0.08 USD/Wdc (Feldman et al., 2021). For modules with a DC power range between 250 and 500 W, the racking cost for conventional system is between 20 USD and 40 USD per module, dwarfing the 37 cents per module of the stainless-steel zip ties. In terms of energy production, the output of tilted ground-mounted PV is higher than that of the vertical fence PV as shown in Fig. 21. However, because the vertical fence PV drastically reduces the cost of material involved in the structural balance of systems, the LCOE of the vertical fence PV is competitive with the LCOE of optimized ground-mounted PV. As shown on Fig. 22, when the right orientation is chosen for the vertical fence PV (due South in this case), the LCOE of the vertical fencing PV (0.035 USD/kWh is lower that the LCOE of the ground-mounted PV (0.038 USD/kWh). As a result, vertical fencing can be cost-effective if well designed, adding value to existing farm structures. It should be further stressed that the +/- 45 deg range of the LCOE equivalent to optimized version is important as it indicates the reduced cost of the fence mounted option offsets the optimization of the more expensive rack for a significant range off due South. The lifetime PV energy generated per linear meter of fence is between 1.3 MWh/m and 2.6 MWh/m using a low power density module and a high-power density module, respectively.

4.2. Applications for farming

The PV racking system described here is a relatively easy retrofit that farmers could do on the mechanical systems themselves for both the retrofit systems as well as installing new fencing for this purpose on the exterior of fields. This system also provides the opportunity to use the PV module fence as windbreaks. In this way farmers would build fences around fields meant for crop protection because windbreaks reduce soil erosion (Bates, 1944; Cornelis & Gabriels, 2005), improves water-use efficiency (Cleugh, 1998), increases crop quality and crop yield (Brandle et al., 1992; Brandle et al., 2004; Hodges & Brandle, 1996), and rebuilds soil carbon (Wiesmeier, et al. 2018). These benefits might also occur with the addition of a solar fence acting as a windbreak. Future work is needed to quantify these benefits with modeling and experimental studies.

4.3. Limitations and Future work

Research into the electrical optimization of vertical fence-based retrofit PV racking is promising for small-scale systems (Hayibo and Pearce, 2022), but future work is needed to model and optimize large scale farms. Future work is also needed to test this system over the long term for different semiconductor and module types including flexible modules in a range of geographical locations to capture any issues that might arise with environmental conditions. Installation time tests could also be compared to industrial standards to determine labor costs. This application also provides an economic opportunity to make agrivoltaic fence specific modules with long wire leads for fences with long spacing between vertical supports. Finally, a GIS study is needed to determine both the potential PV capacity (as well as the increased agricultural output for PV windbreaks) for using this model both on animal farms as well as windbreaks for both the U.S. and the rest of the world. This latter point should perhaps be stressed. Currently the value of windbreaks is well known for farming but the cost to install them needs to be offset by increased agricultural output. The economic value density of PV is much higher than agricultural farming (e.g. grapes (Malu et al., 2017)), so solar electricity revenue generated windbreaks demand a far more thorough analysis. Additionally, the shear and overturning moments calculated are for fence like (vertical) applications only and should not be used for other racking types. Additional analysis maybe required to verify the fence posts and foundations can withstand the shear and overturning moments calculated for a given site and fence construction.

5. Conclusions

The results of this study clearly show that retrofitting existing farm fencing for a wide range of farms including sheep, goats, pigs, cows, and alpaca in the U.S. to operate as vertical PV racking is mechanically technically viable. The maps generated from the mechanical wind loading analysis provide guidance to farmers and installers to determine the safe PV density for a given fence in a given location. Most strikingly, these retrofits offer the potential to install PV for racking costs below 1 cent (USD) per Watt and active revenue-generating wind breaks. Even for non orientation optimized fences the LCOE for fence-based racking can be lower for optimal oriented and tilted PV systems using the same modules. Furthermore, testing on the field has shown that the installation of the PV module is fast and easy as two people were able to install 3 modules on a fence in 7 min in a non-ideally cold weather and the removal of the modules was accomplished in 2 min. This provides added benefits for small farmers who opt for fence-based PV in the futures, as they can radically reduce the installation costs.. Future work is necessary to determine the full scope of the benefits of this approach of vertical PV agricultural fencing on a global scale.

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.

Acknowledgements

This work was supported by the Thompson Endowment.

Appendix A. .

A.1 Calculation of fence epsilon:

Fence epsilon is the ratio of fence fabric/mesh area to the total area of the fence. The fence epsilon can also be defined as the complementary of the porosity (epsilon + porosity = 1). For example, let us take a chain link fence of 2 in. sides and a fence wire of 0.01 in. as shown in the Fig. A1.

From the above illustration, let the area of a section of fence be 0.05*0.05 m or 2*2 in., i.e. 0.0025 square meter or 4 square inches. Now the area covered by the wire of 0.01 in. on the four sides of the chain link diamond is 4*(0.01*2) i.e., the 0.08. Thus, the fence epsilon will now be 0.08/4 i.e. 0.02. Similarly, it can be calculated for other fence fabric types too.

A.2 User inputs

The text form for the “WL_WireFence.py” is as follows:

```
from Data_Fence import Data_Fence.
# Initial Data.
myFence = Data_Fence(Fence_Top_ft = 3.5,
Fence_Bottom_ft = 0.0,
Fence_Seg_Width_ft = 8.0,
Fence_Seg_Cnt = 6,
Fence_Epsilon = 0.05,
PV_Panel_Height_ft = 3.0,
PV_Panel_Width_ft = 4.0,
Loc_Vel_mph = 120,
Loc_Exp_Category='B',
Loc_Elev_ft = 250,

)

# Calculate Moment and Shear force @ Base for Pole.
print(f'Base Shear force = {myFence.Base_Shear:.2f} lbf').
print(f'Base Moment = {myFence.Base_Moment:.2f} ft-lbf').
```

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