Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops

Kelsey Horowitz, Vignesh Ramasamy, Jordan Macknick and Robert Margolis

National Renewable Energy Laboratory

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15013 Denver West Parkway
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List of Acronyms

BOS	balance of system
DC	direct current
EPC	engineering, procurement, and construction
GCR	ground coverage ratio
KW_{DC}	kilowatts-direct current
LCOE	levelized cost of energy
MW_{AC}	megawatts-alternating current
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
PV	photovoltaic
PVCS	PV combining switchgear
SMART	Solar Massachusetts Renewable Target
W_{DC}	watts-direct current

Executive Summary

Today, most utility-scale solar photovoltaic (PV) systems are sited over bare ground, with existing vegetation removed and new vegetation discouraged using herbicides or gravel. However, this practice can result in environmental degradation and habitat loss. Colocating PV with other land uses such as growth of pollinator-friendly plants, grazing, or crop growth can help mitigate some of these impacts. Additionally, this "dual-use" PV approach can help reduce land-use competition between agricultural activities and PV development in certain areas and can, in some locations and for some applications, provide synergistic benefits to the PV system and agricultural activity. Despite these potential benefits of colocation, little is currently known about the *cost* and economic feasibility of using these types of approaches.

In this report, we conduct bottom-up analysis of the installed costs for different *ground-mounted* (as opposed to PV installed on greenhouses, farmhouse rooftops, and other structures) dual-use PV designs and applications. We estimate an installed cost premium of \$0.07/W_{DC} to \$0.80/W_{DC} for dual-use PV systems over conventional ground-mounted PV systems installed over bare ground. The highest premiums are for PV + crop use cases because of the use of modified PV support structures. In all cases, site investigation costs are higher because of the additional effort needed to plan and design for these more complex installations and to coordinate across additional stakeholders (e.g., farmers). We found that PV efficiency and ground coverage ratio are important system cost drivers, particularly for the PV + crop applications, which have higher balance-of-system costs; improving these inputs could help reduce installed costs in the future. Overall, because dual-use PV deployment is in an early stage, additional experience and best practice development may help bring system costs down toward the cost of conventional ground-mounted PV applications.

Understanding these capital costs is only a first step toward better understanding the economic feasibility of dual-use PV. Additional data on factors like crop yield changes, water use efficiency impacts, effects of ground cover on PV panel temperatures, and operation and maintenance costs are needed to assess the lifetime cost and revenue effects of dual-use PV and truly understand the value proposition of these approaches under different scenarios.

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1. Introduction

Today, most utility-scale solar photovoltaic (PV) systems are sited over bare ground, with existing vegetation removed and new vegetation discouraged using herbicides or gravel. This practice is also employed for many smaller, ground-mounted commercial or community solar facilities. However, doing so can result in environmental degradation and habitat loss (Hernandez et al. 2014). In addition, although U.S. and global electricity needs could be offset with PV systems that use only a small fraction of available land (Ong et al. 2013), land-use competition still arises because agricultural or conservation lands are also often very desirable PV development sites.

PV systems are most productive in areas with high irradiance, light wind, low humidity, and moderate temperatures, where the conditions can correlate with croplands (Elnaz H. Adeh et al. 2019). Agricultural land also tends to be flat and cleared of trees, and thus desirable for PV installations. The resulting land-use competition is particularly pronounced in smaller countries and states. Also, the inclusion of distributed generation requirements as part of state renewable portfolio standards (Donalds 2017) could increase land use competition depending on the amount of rooftop PV installed.

There can also be benefits to colocation of PV and other land uses, even where land use competition is not a concern (Hernandez et al. 2019; Macknick et al. 2013; Schindele et al. 2020). Colocating PV with farmland, known as “agrivoltaics,” can provide a steady source of income to complement farm revenue, which can be volatile (Key, Prager, and Burns 2017). Early studies also suggest that agrivoltaics installations could also provide other benefits. For example, water usage for some crops and grasses appears to decrease when the crops are located below PV panels, with greater water savings achieved in arid regions (Elnaz Hassanpour Adeh, Selker, and Higgins 2018; Liu et al. 2019; Marrou, Dufour, and Wery 2013; Elamri et al. 2018; Barron-Gafford et al. 2019). One study found that PV panels with crops grown below were on average 8.9 ℃ cooler during daylight hours than panels without crops. Because PV panels run more efficiently at lower temperatures, this finding has potential implications for PV energy yield, particularly in hot climates (Barron-Gafford et al. 2019). Early studies have also indicated that yields of some crops can increase under PV panel shade depending on climate and agrivoltaic system design, particularly in arid regions (Barron-Gafford et al. 2019) (Amaducci, Yin, and Colauzzi 2018). Although yields decrease for some crops, climates, and system designs (Dupraz et al. 2011; Marrou et al. 2013; Valle et al. 2017), overall the studies to date indicate that agrivoltaics can provide synergistic benefits, particularly with further understanding and optimization of dual-use site designs.

PV installations and animal activities can also be complementary. Increased water efficiency and biomass yield along with the shade of the PV panels can also improve the environment for sheep or cows grazing below the panels, while grazing animals can assist in vegetation management for PV sites (Elnaz Hassanpour Adeh, Selker, Hernandez et al. 2019 and Higgins 2018). Colocating PV with pollinator-friendly groundcover can expand habitat for the dwindling bee population; decline of pollinators has serious implications for global ecosystems and food production (Vanbergen 2018). Pollinator-friendly groundcover can also benefit local agriculture, with a recent study (Walston et al. 2018) showing more than 3,500 km^2 of agricultural land near existing and planned utility-scale solar sties would benefit if those solar projects had pollinator-friendly groundcover.

Several states have begun implementing policies that encourage pollinator-friendly land practices (Terry 2020), and the Solar Massachusetts Renewable Target (SMART) program provides an Agricultural Solar Tariff Generation Unit[1] to incentivize dual-use of agriculture and solar. These programs provide additional benefits to the PV system owners in dual-use applications. Also, the interest in dual-use systems is not limited to the United States; the latest European Commission tender for opportunities in research and innovation specifically mentioned agrivoltaics. Furthermore, Japan has implemented programs for PV and crop applications, called "solar sharing" (Sugibuchi 2019), and China has support policies for controlled environmental agriculture as well as rural economic stimulation that could encourage these dual-use approaches (Xue 2017).

Despite the potential benefits of dual-use PV, little is currently known about its cost. This includes both the capital costs and the operation and maintenance (O&M) costs. There are several ongoing studies around the O&M costs of different dual-use approaches, but to-date there is insufficient data to make firm conclusions. So, in this report, we focus on improving understanding of the capital costs for these projects. We do this by utilizing NREL's bottom-up system installed cost model (Fu et al. 2018) to analyze costs of different designs applicable to three dual-use categories: PV colocated with pollinator habitat (without grazing), PV colocated with crops, and PV colocated with grazing. We are specifically focused on ground-mounted applications and not those where PV is located on farm building rooftops, greenhouses, or other structures.

In this report, we first provide a brief overview of the current landscape for dual-use PV. Then we present our analysis of capital costs for a set of benchmark dual-use designs compared to conventional PV systems installed over bare ground. Finally, we conduct extensive sensitivity analysis of various system design parameters, which are not currently standardized. We also look at the sensitivity of results to cost inputs that still contain uncertainty given the nascent stage of this industry.

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[1] "Solar Massachusetts Renewable Target (SMART) Program," https://www.mass.gov/info-details/solar-massachusetts-renewable-target-smart-program

2. Current Landscape of Ground-Mounted Dual-Use PV

2.1 PV + Crops

The dual-use PV industry is still relatively immature compared with the PV industry at large. Approximately 2.8 GW of PV + crop installations exist globally, with most of the capacity located in China, Japan, and South Korea (Schindele 2020). The number of PV + crop projects has increased 16-fold over 4 years in Japan, with a total of 1,511 sites as of 2017 (Sugibuchi 2019). Many of these existing projects are smaller in size than a conventional utility-scale PV project, with a 4.4 MW system being the largest PV + crop project in Japan as of 2019, but a 480 MW project in Nagasaki is under development. Japan requires annual reporting of crop yield impacts for PV + crop sites. No comprehensive public data on PV + crop sites in China or South Korea appear to exist, but a 700-MW PV plant in China's Gobi desert has been converted to an agrivoltaics site with berry bushes grown below the panels ("Agrivoltaics – Solar Panels on Top, Potatoes down Below" 2019).

In the United States, Massachusetts is encouraging dual-use PV applications through its SMART program incentives. As of the writing of this report, the total installed capacity approved under the SMART qualified Agricultural Solar Tariff Generation Unit (includes PV + crops and PV + grazing) is 20.25 MW_{AC} of projects (Palano 2020). These projects, as well as PV + crop projects we are aware of in Europe, range in size from 20 kW to several MW. France has the largest PV + crops capacity in Europe, totaling around 40 MW which includes many small pilot projects (Schindele 2020). Total Quandran announced a goal of developing 500 MW of PV on agricultural lands in France by 2025 (Bhambhani 2020).

PV + crop system designs and applications are not standardized, and a variety of diverse approaches are being explored. System designs are not yet fully mature and are still being iterated on and optimized. These range from bifacial, vertical panels with crops grown between and/or used as fencing for crops or livestock to much more traditional PV system structures without elevated panels and with crops planted only between the panels. There are also multiple designs involving elevated structures that allow harvesting equipment to pass beneath the panels, including "stilt-mounted" designs with thin posts at a lower density, PV panels that allow more light to pass through and traditional PV structures that are reinforced and elevated. We will explore the upfront capital costs of three of these different designs for PV + crops in this report.

2.2 PV + Grazing

A comprehensive set of data on PV + grazing sites installed globally does not currently exist. One challenge is that grazing activities can be alternated with mowing activities, and a site that is grazed one year might not be grazed the next year. Based on primary interviews and web searches, we estimate the U.S. capacity of PV + grazing sites at over 100 MW. The most common type of PV + grazing site involves sheep grazing; however, grazing with other livestock, such as cattle or rabbits, exist as well. A 2.8 MW cattle grazing project is currently under development in Massachusetts. While sheep can fit under the panels without having to modify conventional PV structures, PV + cattle grazing requires elevated and sometimes reinforced structures if the cattle are grazing beneath the panels. Grazing can be provided as an

O&M service to PV companies. Additional information on the current status of and knowledge around PV + grazing can be found on the American Solar Grazing Association's website.[2]

2.3 PV + Pollinator Habitat

Pollinator-friendly PV is much more established in the United States than PV + crop or PV + grazing applications. Based on data collected through primary interviews and web searches, NREL estimates over 1 GW of PV + pollinator habitat has been installed in the United States. Some of this development is driven by the pollinator-friendly PV policies discussed in the introduction (Terry 2020). Although PV system designs for this application are relatively standardized, best practices are still not established for seeding, types of seed to use, soil care, herbicide application and vegetation management, erosion control, and other factors. Hence, site preparation activities for PV+ pollinator habitat facilities vary much more across sites than do site preparation activities of traditional PV facilities over bare ground or turf grass.

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[2] "Research," American Solar Grazing Association, https://solargrazing.org/resources/

3. Scenarios Modeled and PV Design Assumptions

We model PV installed costs for the following different scenarios (Figure 1) in this report:

- **Conventional PV** installed over bare ground as a baseline. We look at both fixed and 1-axis tracking conventional PV designs. This is the default configuration used in NREL PV system cost analyses.
- **PV + grazing**, including both fixed-tilt and 1-axis tracking approaches. These scenarios have the same configuration as conventional PV, but they use pasture grasses or in some cases use both pasture grasses and pollinator-friendly vegetation below the panels instead of bare ground.
- **PV + pollinator habitat**, including fixed-tilt and 1-axis tracking designs, with the same structure as conventional PV but with pollinator-friendly vegetation below the panels instead of bare ground.
- **PV + crops**. We look at the following three designs for PV + crops: 1) vertical mount structures with bifacial PV panels, 2) a stilt-mount design with tracking, and 3) a structure similar to that of conventional PV but reinforced to enable increased panel height. For all of these designs, the crops can be grown under and/or between the panels at different densities.

For each scenario, we benchmark a 500 kW_{DC} system as a base case system and explore the sensitivity of installed system cost to system size in MW_{DC}. Each scenario has a set of benchmark assumptions (Table 1), which include the design parameters (Table 2) illustrated in Figure 2. These assumptions are based on current typical or median values based on our interviews with dual-use PV developers and installers. However, these parameters can vary across systems depending on the needs of a specific project, so we conduct sensitivity analyses in Section 5.2 to the panel spacing, ground clearance, and ground coverage ratio (GCR).

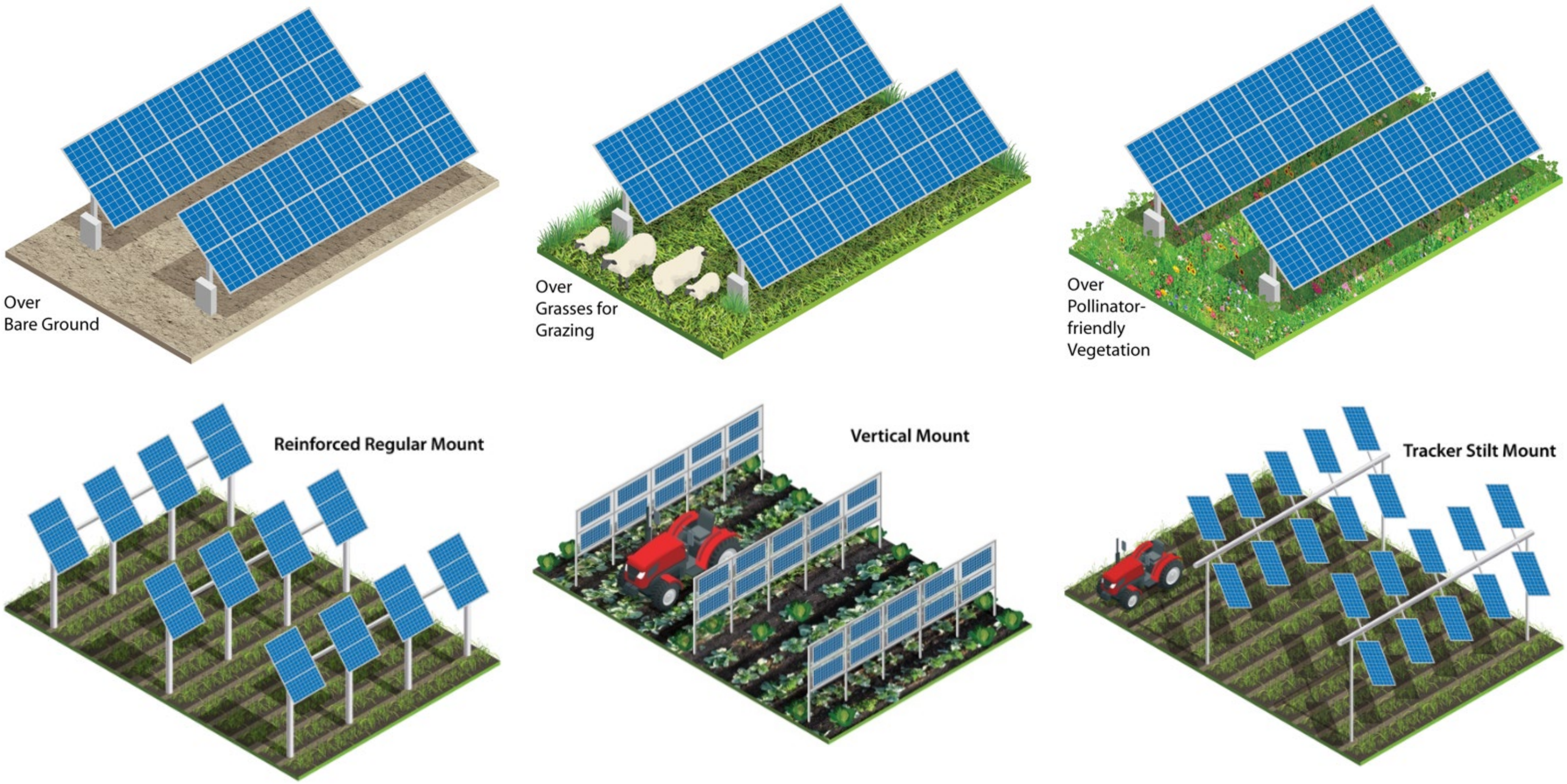

Figure 1. Illustrations of the system designs modeled for each dual-use PV scenario

Table 1. Benchmark Model Assumptions for Each Scenario

	Conventional PV	**PV + Pollinator Habitat** (no grazing)	**PV + Grazing**	**PV + Crops** (Reinforced)	**PV + Crops** (Vertical)	**PV + Crops** (Stilt)
Groundcover type	Bare ground	Pollinator-friendly vegetation	Grass, other pollinator-friendly vegetation	Crops	Crops	Crops
Structure type	Conventional	Conventional	Conventional	Reinforced Regular Mount	Vertical	Tracker Stilt-Mount
Fixed tilt or tracker	Both	Both	Both	Fixed	Fixed	Tracker
Inter-panel spacing (ft)	0	0	0	2	0	2
Ground clearance (ft)	4.6	4.6	4.6	8.2	6.4	8.2
Inter-row spacing[a] (ft)	16.6	16.6	16.6	31.2	28.3	32.4
Ground Coverage Ratio (%)[b]	33% tracker, 44% fixed-tilt	33% tracker, 44% fixed-tilt	33% tracker, 44% fixed-tilt	28%	<1%	20%
Module Efficiency %	19%	19%	19%	19%	21%	21%
Power density (acre/MW)	5.9 tracker, 4.5 fixed-tilt	5.9 tracker, 4.5 fixed-tilt	5.9 tracker, 4.5 fixed-tilt	9.8	7.0	13.8

[a] The inter-row spacing is calculated assuming a 44-degree tilt for all designs except for the vertical mount (which assumes a 90-degree tilt).

[b] The GCR for vertical mount is negligible, as the solar panels are mounted at right angle to the ground.

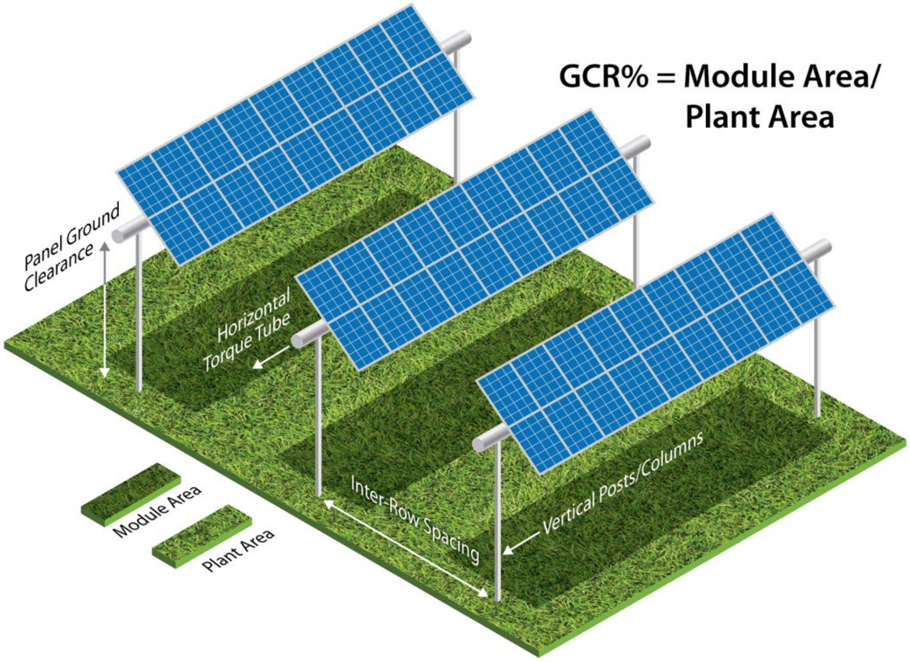

Figure 2. Diagram of system design parameters referenced in this report

Table 2. Details of Structural Assumptions for Each Mounting Structure Analyzed

Mounting Structure	**Regular**	**Regular**	**Vertical Mount**	**Reinforced Regular Mount**	**Tracker Stilt Mount**
Fixed-Tilt/Tracker	Fixed	1-Axis-Tracker	Fixed	Fixed	2-Axis-Tracker
Acre/MW	4.5	5.9	7.0	9.8	13.8
Horizontal Tubing	4"x4"x0.137" Round	4"x4"x0.137" Round	2.4" x 1.8" Steel Channel tube	4" x 4" x ¼" Round	4"x4"x0.137" Round
Horizontal Tubing lb/ft	7.2	7.2	3.6	12.2	7.2
Tubing $/ft	$3.7	$3.7	$2.1	$6.3	$3.7
Horizontal Tubing Ft	3961	3961	3740	3444	1840
Vertical Post	W6 x 15 Wide Flange	W6 x 15 Wide Flange	6.2" X 2.4" X 0.98" C Channel	8" Sch 40 Structural Pipe	W6 x 15 Wide Flange
Vertical Post lb/ft	15	15	7.5	28.5	15
Pipe $/ft	$6.3	$6.3	$7.5	$23.9	$6.3
Vertical Posts #	157	157	726	230	77

4. Capital Cost Modeling Methodology

We use NREL's bottom-up modeling methodology to calculate the capital costs associated with each application and system design type. This approach involves mapping out all steps in the installation process and determining the labor, materials, and equipment required per step. We also add overhead costs and profit. However, project financing costs are not included in the upfront system cost estimates. This methodology is documented in detail for conventional PV systems in NREL's annual PV system cost benchmark report (Fu, Feldman, and Margolis 2018). For this analysis, we modify the conventional model to reflect the differences in system assumptions documented in Table 1. Our results use U.S. cost assumptions for labor ("National Occupational Employment and Wage Estimates United States" 2019).

4.1 Data Sources

Input data for our bottom-up models comes mainly from primary interviews with PV developers and installers. We interviewed personnel from 10 companies: seven U.S. companies and three European companies. We supplement the interview data with unit cost data from standard construction cost guides (Mewis 2019). We have a limited number of input data points for nonconventional system designs in the PV + crop space, and so the costs associated with those applications are more uncertain. PV installed system costs are based on a simple average of modeled costs in Oregon, Arizona, Michigan, Massachusetts, New York, Connecticut, California, and Illinois. We chose these eight states, because they currently have one or more types of dual-use PV systems installed and they represent a range of installed costs.

5. Results and Discussion

5.1 Benchmark Results

The U.S. installed costs for our benchmark systems are shown in Figure 3 (page 11). All dual-use PV scenarios have a higher installed capital cost than scenarios with typical PV and a conventional structure installed over bare ground. The smallest price premium is associated with PV + grazing systems, which can use conventional PV structures and do not require as much site preparation or seeding, as is the case with pollinator-friendly PV. However, the PV + grazing results shown here are for sheep grazing, which is currently more common; cattle grazing scenarios are expected to be more expensive because of the need to elevate the panels and, in some cases, reinforce the system structure. The sensitivity of installed costs to panel ground clearance is explored in Section 5.2 and can inform potential costs premiums for PV + cattle grazing. The reinforced regular mount structure used for some PV + crop installations, which is elevated and reinforced, could also apply to cattle grazing applications.

In our model, the reinforced regular mount structure has the highest installed costs per watt owing to the use of more expensive heavy-duty materials (Table 2, page 8). The structure currently is reinforced in these designs to hold the panels 8.2 ft above the ground while maintaining structural integrity under wind and snow loads. However, this design is a relatively early iteration, and it is possible that future design optimization could reduce additional structural costs. In fact, the tracker stilt-mount design also used for PV + crop growth can also involve panel heights of 8.2 ft but reduces materials, labor, and installation equipment costs by reducing the number of supports and horizontal tubes. The vertical mount system has the lowest installed cost among the PV + crop scenarios, but it could produce less energy per rated watt because of the panel orientation. Lower energy production increases the levelized cost of energy (LCOE) and affects lifetime system economics; the tradeoff between installed cost and LCOE of dual-use systems requires further study.

For all PV + crop structure types, developers often tend to design the systems to be compatible with the growth of various crops and harvesting practices. This approach can increase costs compared with designing for a single crop or set of crops, for example, by requiring higher panels or additional panel spacing, but it can be necessary to accommodate uncertainty related to farming practices and evolving agricultural markets.

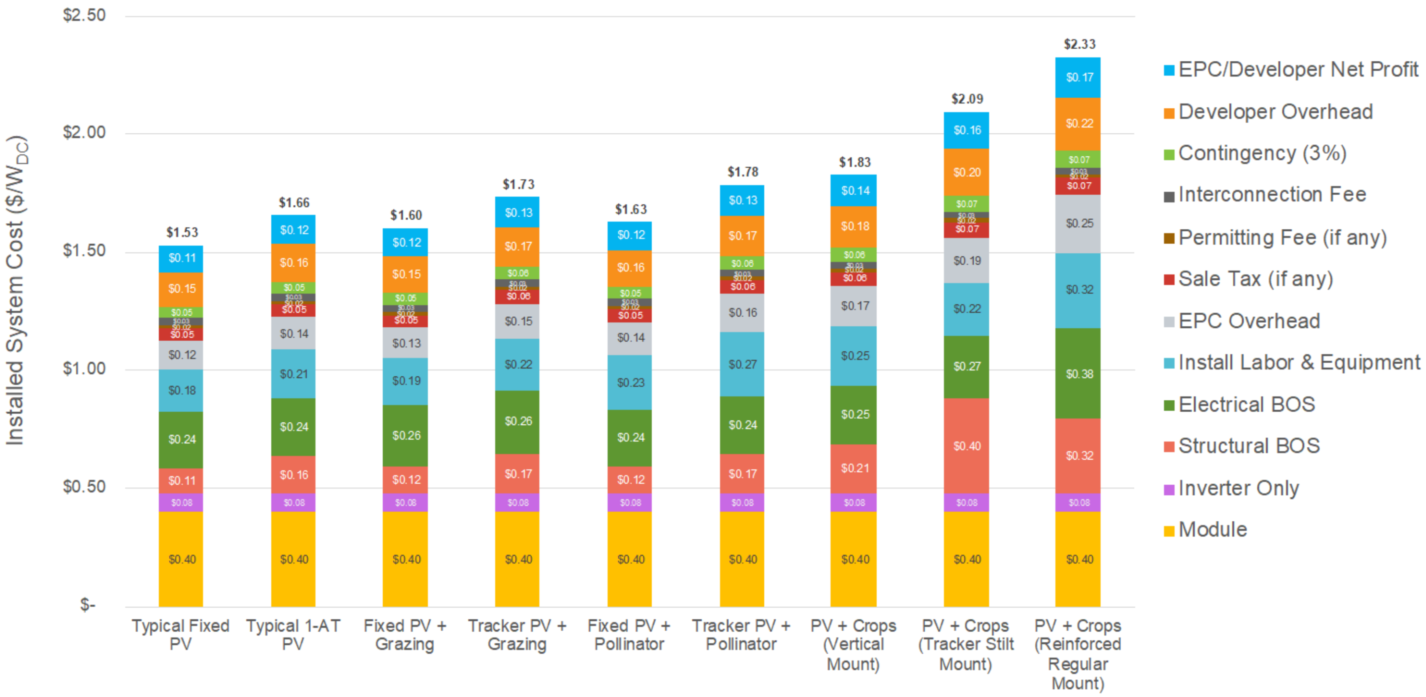

Figure 3. PV installed system costs for each dual-use scenario with benchmark assumptions for a PV system with 500 kW rated power

Costs are based on a simple average of modeled costs in Oregon, Arizona, Michigan, Massachusetts, New York, Connecticut, California, and Illinois—states that currently have one or more types of dual-use PV systems installed.

Figure 4 details the breakdown of balance-of-system costs and illustrates the influence of installation labor and equipment costs in driving cost differences between applications. Differences in the cost of the racking structures are also important among the PV + crop scenarios; however, much of the racking structure in the stilt-mount case is included under the "tracker" cost category. The elevated, reinforced regular mount PV + crop systems we modeled need more pounds of steel than the typical systems, PV + grazing, or PV + pollinator habitat systems because of their panel elevations and atypical support structures. Some PV + crop installations (not modeled here) use conventional structures without elevated panels, where crops are grown only between the PV panels or both below and between the panels. However, these tend to be smaller research and development systems, and our interviews indicate that these designs limit the machinery that can be used in harvesting.

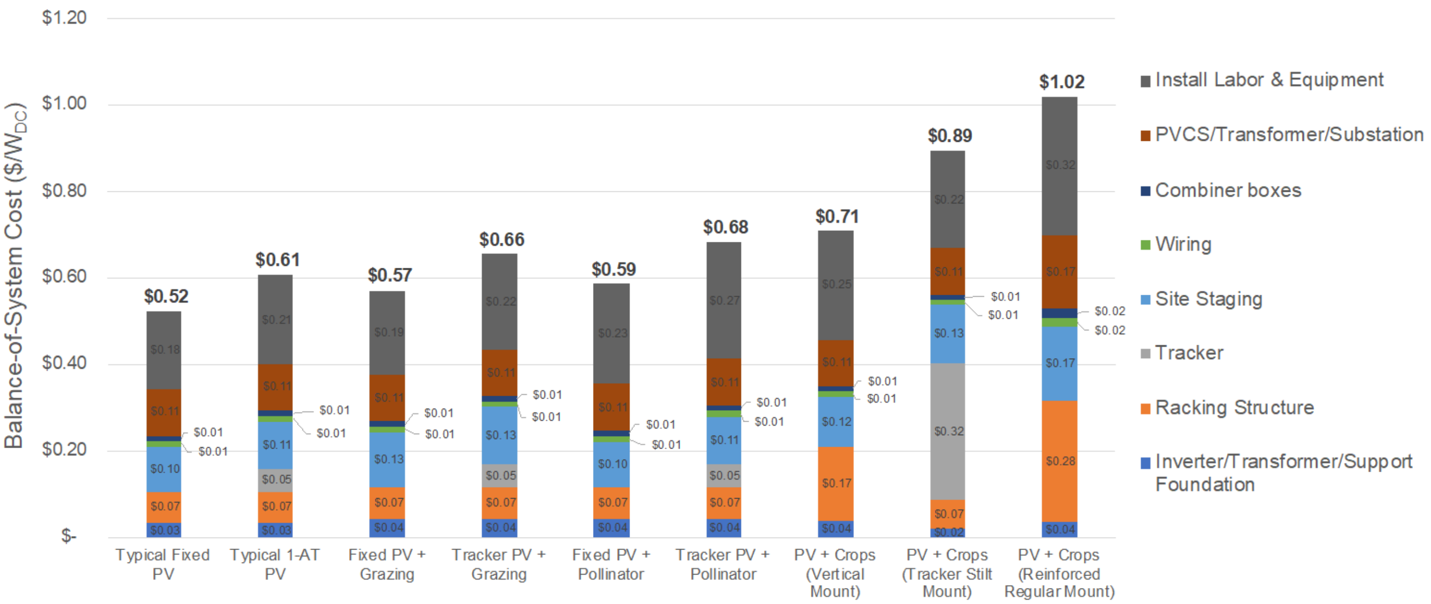

Figure 4. BOS cost breakdown for each dual-use scenario with benchmark assumptions and a PV system with 500-kW rated power

Costs are based on a simple average of modeled costs in Oregon, Arizona, Michigan, Massachusetts, New York, Connecticut, California, and Illinois—states that currently have one or more types of dual-use PV systems installed. Site staging costs include items such as access roads, fencing, temporary office space, and module storage boxes. PVSC = PV Combining Switchgear.

Site preparation costs are included under install labor and equipment and contribute to differences in cost across scenarios. These differences are summarized in Table 3. Crops and grazing incur some additional costs, such as for fencing or a water well for grazing animals; the fencing premium is higher for the PV + crop scenario because farmers want extra fencing underground to protect crops from wildlife. All three dual-use PV approaches have an increase in site investigation costs compared to typical PV installed over bare ground owing to additional planning, analysis, and coordination needed to ensure success of the vegetation under the panels. This includes working with, for example, a farm manager who coordinates between developers, regulators, and farmers; researching the implications of panel shading on grasses, pollinators, or crops; and verifying compliance with dual-use incentive program requirements. There is insufficient data at this point to differentiate site investigation costs between applications.

Compared with PV over bare ground, the PV + grazing and PV + crop scenarios reduce some site preparation costs, including costs related to clearing and grubbing, soil compaction, and soil stripping and stockpiling. Pollinator-friendly PV is typically installed on land where pollinator habitat was not previously grown and thus some additional soil preparation is required compared to the PV + crop or PV + grazing scenario where we assume the land was previously used for either crop growth (for PV + crops) or grazing (for PV + grazing) and thus the soil is already suitable for those applications. Because we assume the land in the PV + crop scenario was previously a farmland (as is the case for the sites that we investigated for this report), grading costs are also lower; these costs are not eliminated because we assume some land preparation activities like leveling and compaction are still required outside the crop growth area for establishing roads, housing inverters and transformers, and so forth. Most of the PV + grazing and PV + pollinator sites would require grading the site to ease the installation process and establishing appropriate grass or pollinator-friendly vegetation to minimize or avoid soil erosion. These site preparation activities appear to be a common practice today, but that could change in the future or vary by site. Best practices to manage soil erosion during the construction phase in these applications are still being developed.

Table 3. Breakdown of assumptions for site preparation, site staging, and structural work differences by dual-use application. Costs are shown as a percent difference from typical PV (500 kW_{DC}) installed over bare ground.

Cost Category	Baseline Value	PV + Grazing	PV + Pollinator	PV + Crops
Fencing	$16,843	+10%	0%	+20%
Water Well*	$0	+100%	0%	0%
Site Investigation	$3,644	+100%	+100%	+100%
Clearing & Grubbing	$6,349	-20%	+50%	-50%
Soil Stripping & Stockpiling	$2,245	-20%	+50%	-70%
Grading	$5,963	+50%	+50%	-50%
Soil Compaction	$2,415	-30%	+50%	-80%
Column Foundation	$17,084	+50%	+50%	-80%

*PV + Grazing sites require a water well setup, which is not mandatory in other dual-use PV applications. 0%–100% in PV + Grazing is equal to $0–$10,000 while in other use cases 0% refers to no change to existing base case value.

Our interviews with dual-use PV developers and policymakers working in agrivoltaics indicate no observed difference in permitting or related soft costs for dual-use installations compared with traditional installations to-date.

Figure 5 shows how total installed system costs vary for each application as a function of PV system rated power. Larger systems benefit significantly from economies of scale across all scenarios. Additional benefits from economies of scale would be observed by increasing system sizes further.

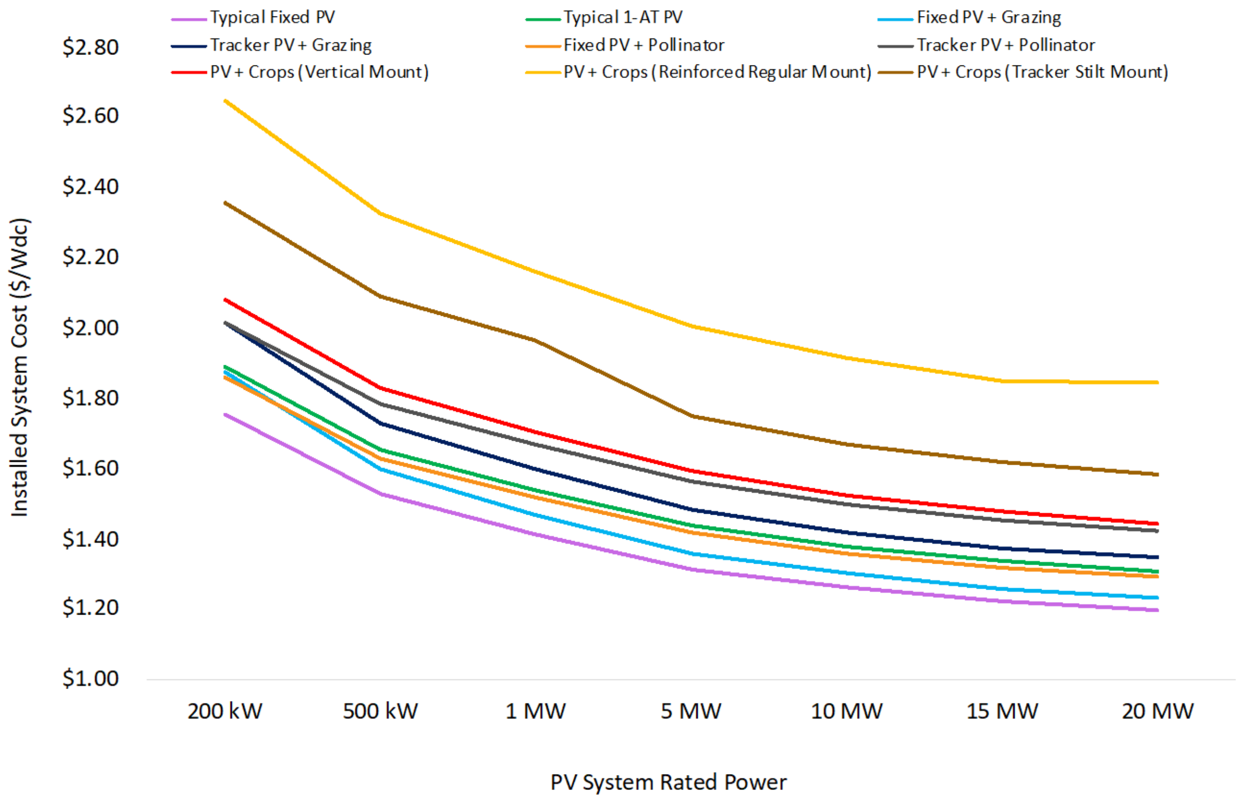

Figure 5. Installed system costs versus PV system rated power (DC) by scenario

5.2 Sensitivity Analysis

Some of our input data are uncertain due to the relative newness of dual-use PV applications. Additionally, our benchmark scenarios above do not capture all the variability among projects in structural design, site requirements, and other factors; this variability is expected to be much larger than the variability for traditional PV applications. To help account for this uncertainty, Figure 6 shows the effect of a +/- 25% change in key input variables on PV system installed cost for different structure types. We observed that the sensitivity for the conventional structure was similar whether the PV was built over bare ground, pollinator-friendly vegetation, or grass for grazing. The reinforced regular mount and tracker stilt-mount systems are more sensitive to changes in efficiency than the other designs because of their higher BOS costs, although efficiency is the major driver of cost in all scenarios.

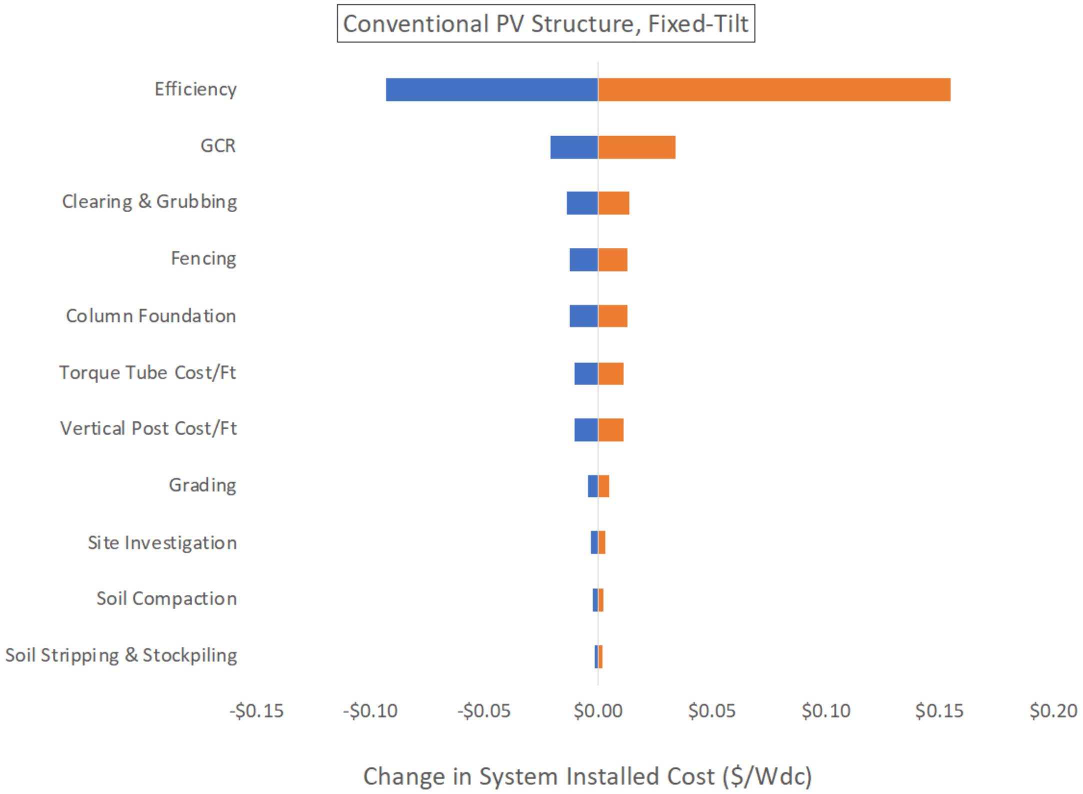

Figure 6.a

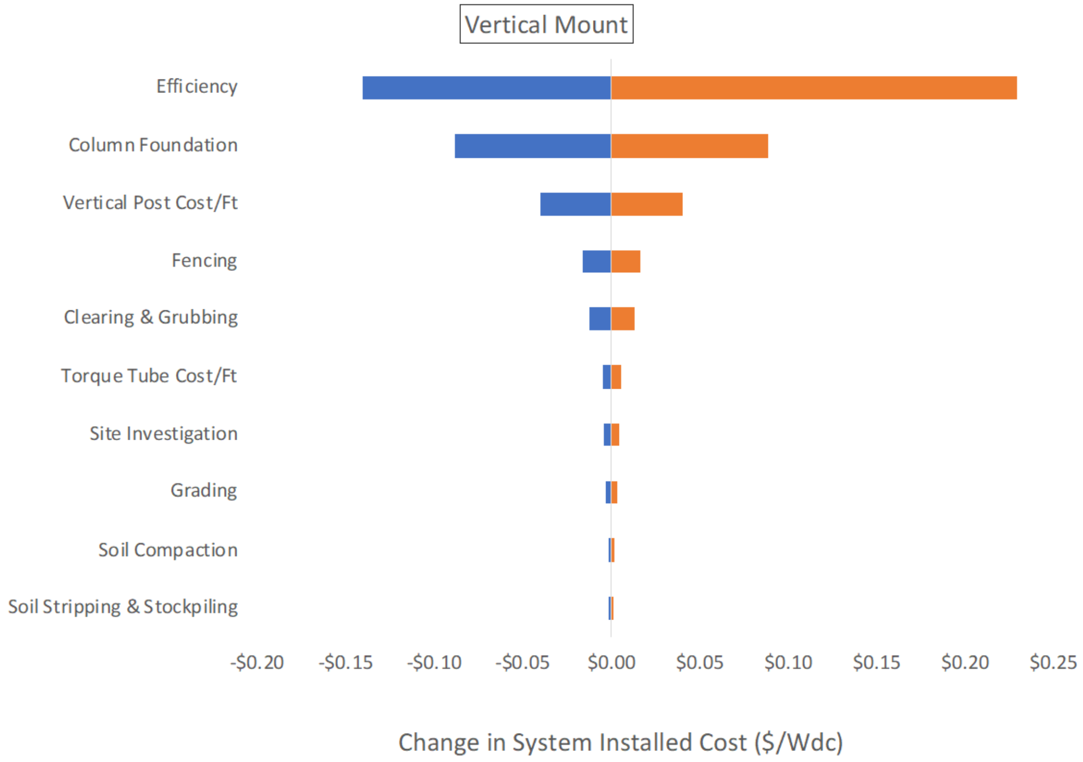

Figure 7.b

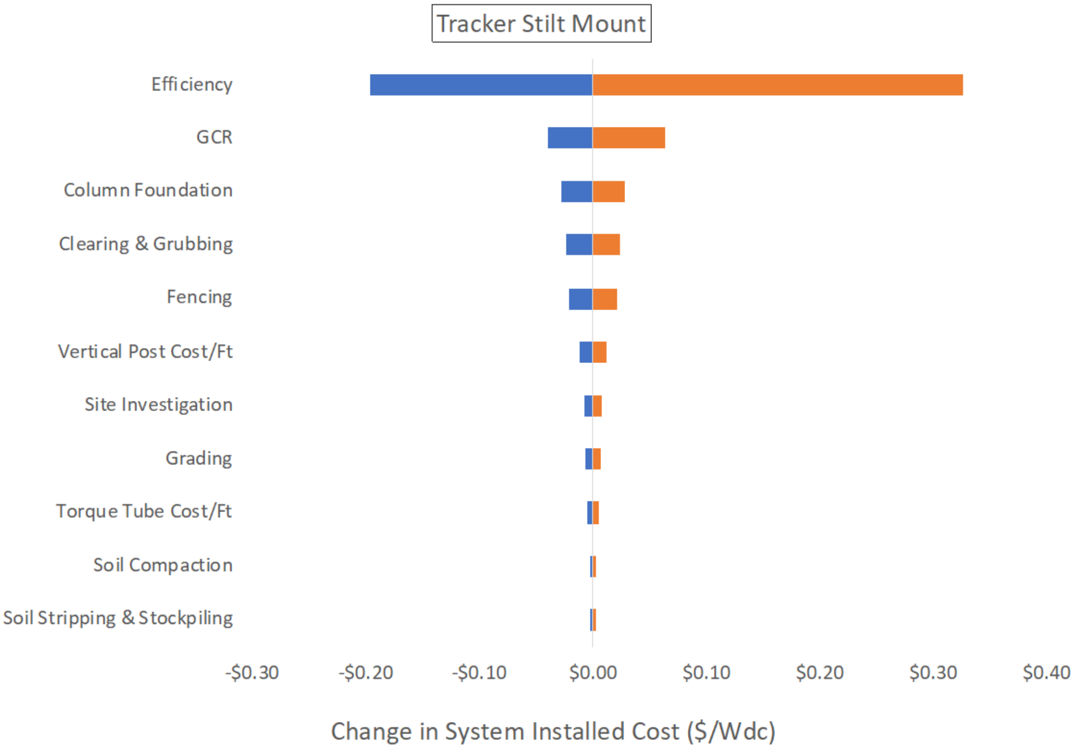

Figure 8.c

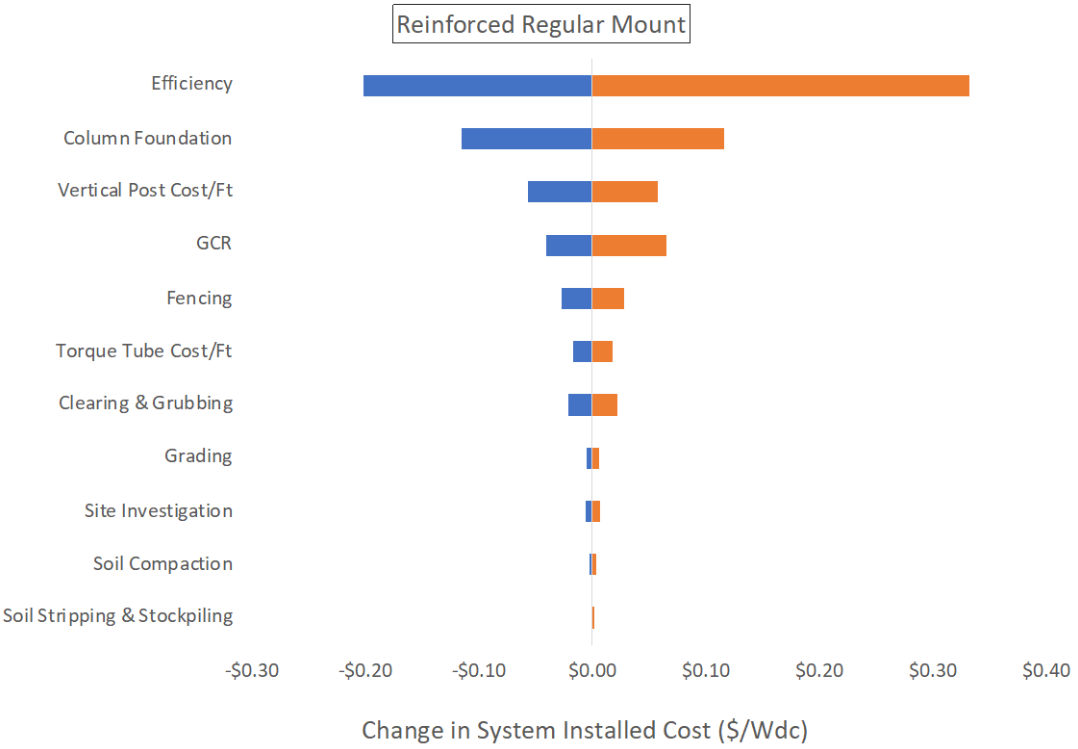

Figure 9.d

Figure 10. Tornado charts showing the sensitivity of total installed costs to +/- 25% changes in key input parameters for the for each structure type

GCR also plays an important role and is often determined by the needs of the specific application (e.g., whether a specific amount of shading is needed to optimize crop growth below the panels). Figure 7 shows changes in system installed cost due to changes in three input parameters often varied in dual-use designs to accommodate specific site needs: GCR, panel ground clearance, and inter-panel spacing. Our benchmark PV + crop scenarios assume GCRs of 20%–28%. A new design from at least one PV + crop company uses a higher GCR of 44% and is expected to reduce installed costs; further investigation is needed to determine the overall impact of this innovation on lifetime costs and revenues given the effects on different crops in different locations. Similar to GCR, these parameters can be varied from site-to-site depending on the needs of a specific farm based on its climate and what crops are being grown. However, developers often attempt to create systems that can accommodate multiple types of crops (rather than optimizing to a single crop) because of the uncertainty surrounding crop demand and prices and the need for farmers to respond flexibly to market conditions. The lesser sensitivity of the tracker stilt-mount design to ground clearance height and panel spacing is because the tracker cost drives most of the balance-of-systems premium in this case.

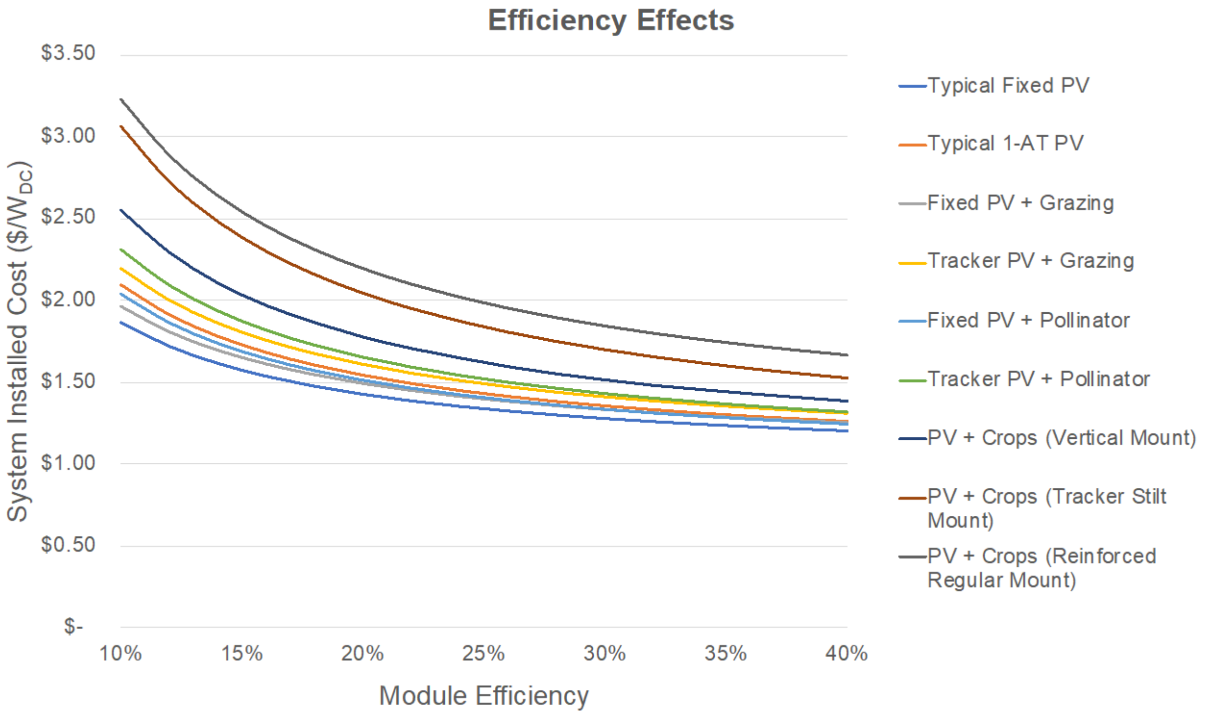

Figure 7.a

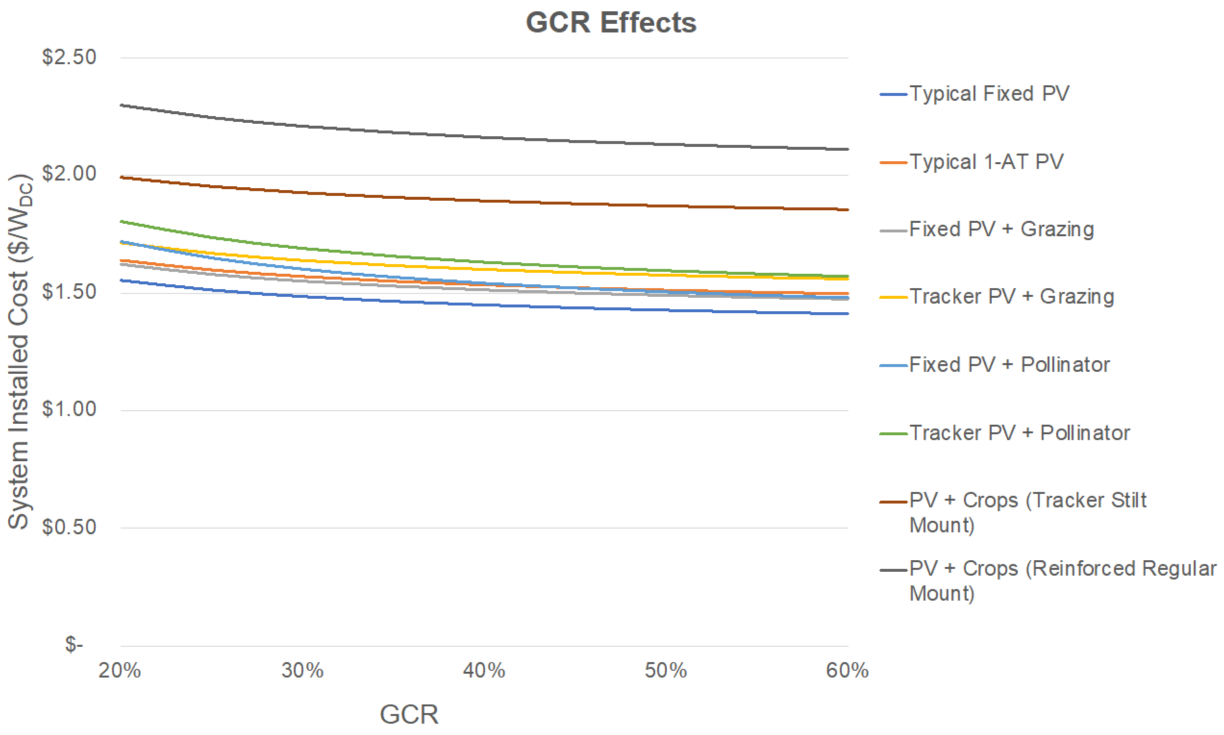

Figure 7.b

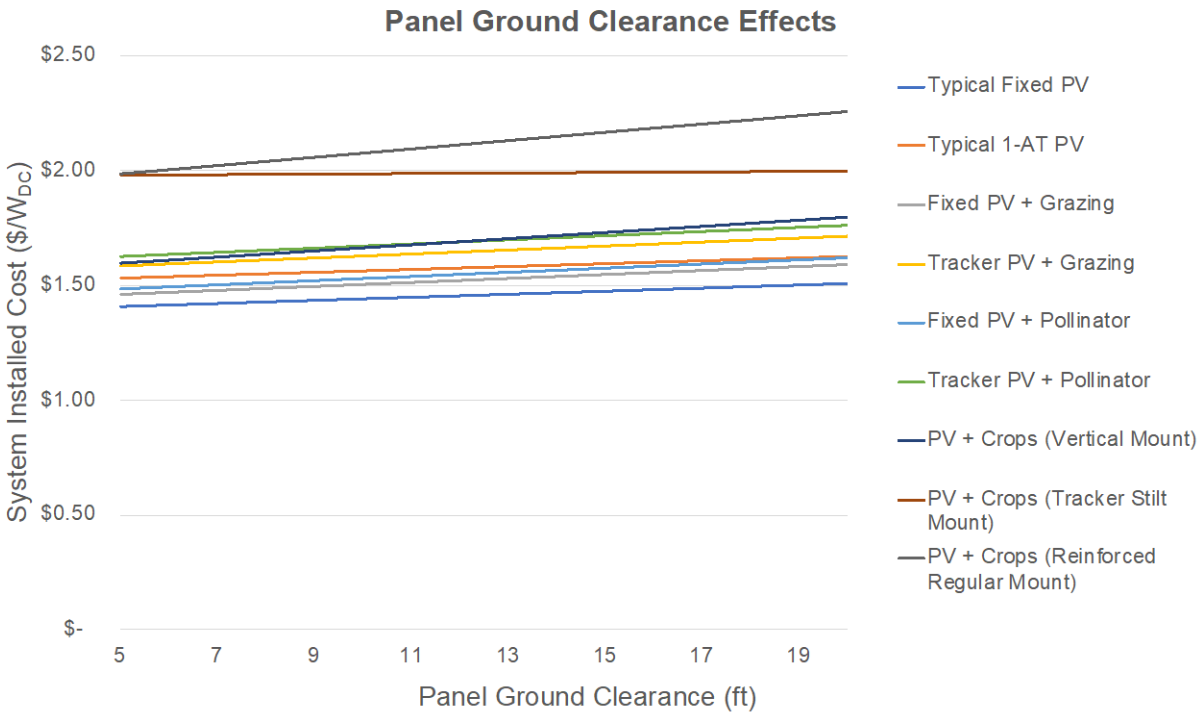

Figure 7.c

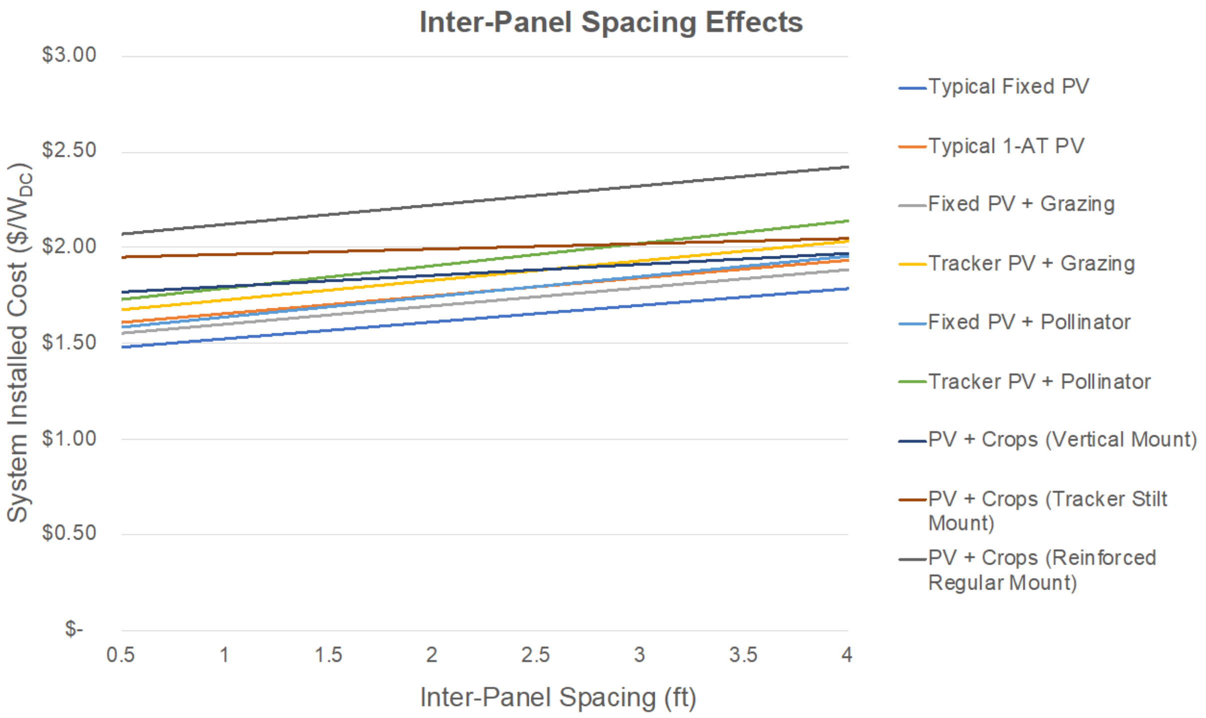

Figure 7.d

Figure 11. Change in system installed cost with changes in input parameters often varied in dual-use designs to accommodate the needs of a specific site

6. Conclusions and Future Work

Based on our bottom-up cost model, we estimate an installed system capital cost premium of $\$0.07/W_{DC}$ to $\$0.80/W_{DC}$ for various ground-mounted dual-use PV scenarios, compared with conventional ground-mounted PV installed over bare ground. The highest premiums are for PV + crop applications because of the use of modified PV support structures. For all dual-use PV scenarios, site investigation costs are higher because of the additional effort needed to plan and design for these more complex installations and to coordinate across additional stakeholders (e.g., farmers). We also find that efficiency and GCR are important system cost drivers, particularly for the PV + crop scenarios, which have higher BOS costs; improving these inputs could reduce installed costs in the future. Overall, because dual-use PV deployment is in an early stage, additional experience, best practice development, and new configurations and technologies might help bring system costs down toward the cost of conventional ground-mounted PV applications.

This analysis does not capture the value proposition of dual-use PV approaches. Lifetime analysis of costs and revenues, encompassing the impacts of PV system design and the colocated agricultural activity, is required to understand the economic feasibility of these applications. However, currently available data are insufficient for analyzing the impacts of PV on crop growth, O&M costs, and other lifetime factors. As the necessary data become available, we plan to incorporate cost-benefit analysis with our installed system cost results of dual-use PV systems.

References

Adeh, Elnaz H., Stephen P. Good, M. Calaf, and Chad W. Higgins. 2019. “Solar PV Power Potential Is Greatest Over Croplands.” *Scientific Reports* 9 (1): 1–6. https://doi.org/10.1038/s41598-019-47803-3.

Adeh, Elnaz Hassanpour, John S. Selker, and Chad W. Higgins. 2018. “Remarkable Agrivoltaic Influence on Soil Moisture, Micrometeorology and Water-Use Efficiency.” *PLOS ONE* 13 (11): e0203256. https://doi.org/10.1371/journal.pone.0203256.

“Agrivoltaics: Solar Panels on Top, Potatoes down Below.” 2019. *En:Former* (blog). November 22, 2019. https://www.en-former.com/en/agrivoltaics/.

Amaducci, Stefano, Xinyou Yin, and Michele Colauzzi. 2018. “Agrivoltaic Systems to Optimise Land Use for Electric Energy Production.” *Applied Energy* 220 (June): 545–61. https://doi.org/10.1016/j.apenergy.2018.03.081.

Barron-Gafford, G., A. Salazar, L. V. Phelps-Garcia IV, L. Lopez, I. Barnett-Moreno, W. Cooke, M. S. Thompson, et al. 2019. “Co-Locating Agriculture and Solar Power Renewables (Agrivoltaics) to Create a More Sustainable Food, Energy, and Water Future.” *AGU Fall Meeting Abstracts* 41 (December). http://adsabs.harvard.edu/abs/2019AGUFM.B41B..01B.

Bhambhani, Anu. 2020. “Agrivoltaics: Total Quadran To Develop 500 MW Solar PV Capacity in France by 2025 On Agricultural Land in Partnership with Agricultural Cooperative Union InVivo Group.” *TaiyangNews*, March 6, 2020, sec. Markets. http://taiyangnews.info/markets/total-quadran-to-explore-agrivoltaic-segment-in-france/.

Donalds, Samantha. 2017. “Distributed Generation in State Renewable Portfolio Standards.” https://www.cesa.org/wp-content/uploads/DG-RPS.pdf.

Dupraz, Christian, G. Talbot, Hélène Marrou, Jacques Wery, Sébastien Roux, Liagre Fabien, Y. Ferard, and A. Nogier. 2011. “To Mix or Not to Mix: Evidences for the Unexpected High Productivity of New Complex Agrivoltaic and Agroforestry Systems.” In , 202–3.

Elamri, Y., B. Cheviron, J. -M. Lopez, C. Dejean, and G. Belaud. 2018. “Water Budget and Crop Modelling for Agrivoltaic Systems: Application to Irrigated Lettuces.” *Agricultural Water Management* 208 (September): 440–53. https://doi.org/10.1016/j.agwat.2018.07.001.

Fu, Ran, David Feldman, and Robert Margolis. 2018. “U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018.” NREL/TP-6A20-72399.

Key, Nigel, Daniel Prager, and Christopher Burns. 2017. “Farm Household Income Volatility: An Analysis Using Panel Data from a National Survey.” ERR-226. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/webdocs/publications/82564/err-226.pdf?v=8397.7.

Liu, Yu, Rui-Qi Zhang, Ze Huang, Zhen Cheng, Manuel López-Vicente, Xiao-Rong Ma, and Gao-Lin Wu. 2019. "Solar Photovoltaic Panels Significantly Promote Vegetation Recovery by Modifying the Soil Surface Microhabitats in an Arid Sandy Ecosystem." *Land Degradation & Development* 30 (18): 2177–86. https://doi.org/10.1002/ldr.3408.

Marrou, H., L. Dufour, and J. Wery. 2013. "How Does a Shelter of Solar Panels Influence Water Flows in a Soil–Crop System?" *European Journal of Agronomy* 50 (October): 38–51. https://doi.org/10.1016/j.eja.2013.05.004.

Marrou, H., J. Wery, L. Dufour, and C. Dupraz. 2013. "Productivity and Radiation Use Efficiency of Lettuces Grown in the Partial Shade of Photovoltaic Panels." *European Journal of Agronomy* 44 (January): 54–66. https://doi.org/10.1016/j.eja.2012.08.003.

Mewis, Robert. 2019. *Building Construction Costs with RSMeans Data 2019*. 77th Annual Edition. Gordian.

"National Occupational Employment and Wage Estimates United States." 2019. BLS (Bureau of Labor Statistics). https://www.bls.gov/oes/current/oes_nat.htm.

Ong, Sean, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath. 2013. "Land-Use Requirements for Solar Power Plants in the United States." NREL/TP-6A20-56290. https://www.nrel.gov/docs/fy13osti/56290.pdf.

Schindele, Stephan. 2020. "AgriPV from BayWa r.e.: Leveraging Synergies of Two Sectors." Presented at the Solar Power Europe, Online, April 21. https://www.solarpowereurope.org/wp-content/uploads/2020/04/SolarPower-Europe-webinar-How-solar-can-contribute-to-a-sustainable-European-Agricultural-policy-.pdf.

Sugibuchi, Koichi. 2019. "Solar Sharing: Symbiosis of PV and Agriculture in Japan." Presented at the Intersolar Europe, Munich, May 15.

Terry, Georgena. 2020. "State Pollinator-Friendly Solar Initiatives." Clean Energy States Alliance. https://www.cesa.org/wp-content/uploads/State-Pollinator-Friendly-Solar-Initiatives.pdf.

Valle, B., T. Simonneau, F. Sourd, P. Pechier, P. Hamard, T. Frisson, M. Ryckewaert, and A. Christophe. 2017. "Increasing the Total Productivity of a Land by Combining Mobile Photovoltaic Panels and Food Crops." *Applied Energy* 206 (November): 1495–1507. https://doi.org/10.1016/j.apenergy.2017.09.113.

Vanbergen, Adam. 2018. "Causes and Consequences of Pollinator Decline." Presented at the EU Pollinator Initiative Workshop, Brussels, March 15.

Xue, Jinlin. 2017. "Photovoltaic Agriculture: New Opportunity for Photovoltaic Applications in China." *Renewable and Sustainable Energy Reviews* 73 (June): 1–9. https://doi.org/10.1016/j.rser.2017.01.098.

R.R. Hernandez, S.B. Easter, M.L. Murphy-Mariscal, F.T. Maestre, M. Tavassoli, E.B. Allen, C.W. Barrows, J. Belnap, R. Ochoa-Hueso, S. Ravi, M.F. Allen. 2014. “Renewable and Sustainable Energy Reviews.” Renewable and Sustainable Energy Reviews 29 (January): 766-779. https://doi.org/10.1016/j.rser.2013.08.041.

Stephan Schindele, Maximilian Trommsdorff, Albert Schlaak, Tabea Obergfell, Georg Bopp, Christian Reise, Christian Braun, Axel Weselek, Andrea Bauerle, Petra Högy, Adolf Goetzberger, Eicke Weber. 2020. “Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications.” Applied Energy 265 (May): 114737. https://doi.org/10.1016/j.apenergy.2020.114737.

Jordan Macknick, Brenda Beatty, and Graham Hill. 2013. “Overview of Opportunities for Co-Location of Solar Energy Technologies and Vegetation.” NREL/TP-6A20-60240.

Hernandez, R.R., Armstrong, A., Burney, J. et al. 2019. “Techno–ecological synergies of solar energy for global sustainability”. Nat Sustain 2, 560–568. https://doi.org/10.1038/s41893-019-0309-z

Leroy J. Walston, Shruti K. Mishra, Heidi M. Hartmann, Ihor Hlohowskyj, James McCall, and Jordan Macknick. 2018. “Examining the Potential for Agricultural Benefits from Pollinator Habitat at Solar Facilities in the United States”. Environ. Sci. Technol. 2018, 52, 13, 7566–7576. https://doi.org/10.1021/acs.est.8b00020.

Gerald Palano. (2020, August 12). Personal interview.