ADAPTING AGRIVOLTAICS FOR SOLAR MINI-GRIDS IN HAITI

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ADAPTING AGRIVOLTAICS FOR SOLAR MINI-GRIDS IN HAITI

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ENERGY ACCESS PARTNERSHIP FOR HAITI

As part of a broader collaboration with the U.S. Department of Energy's National Renewable Energy Laboratory, USAID, and its Haiti Mission established the Energy Access Partnership with NREL as a technical collaboration program to provide unique technical support for scaling up and deploying advanced energy systems, particularly mini-grids, and enabling broader energy sector planning and policymaking in Haiti. Activities under this collaboration focus on developing and deploying analytic tools, policy advice, and technical assistance to promote the deployment of advanced energy technologies and systems to enable self-reliant, secure, resilient, and sustainable economic growth in Haiti. Key workstreams include:

- Energy sector policy and planning
- Mini-grid policy and developer support
- Agrivoltaics for mini-grids
- Energy storage and resiliency planning
- Off-grid solar training.

For more information, visit www.nrel.gov/usaid-partnership.

NREL InSPIRE

NREL has developed extensive research and learning for agrivoltaics through its U.S. Department of Energy-funded research project, Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE). Serving as the U.S. Department of Energy's flagship research project in agrivoltaics, the InSPIRE project oversees research at 24 agrivoltaic field sites across the United States, provides foundational services and analyses to the solar and agricultural industry, and provides technical assistance to communities and governments. The InSPIRE project has also undertaken efforts to quantify the benefits of agrivoltaics and record some early best practices while synthesizing lessons learned in its "five Cs" of agrivoltaics framework: climate, configurations (e.g., solar technology, site layout, etc.), crop selection, compatibility, and collaboration (see details and key lessons learned here). InSPIRE is now working to scale agrivoltaic solutions and research in applications across the world. For more information, visit openei.org/wiki/InSPIRE.

For details and key lessons:
www.nrel.gov/docs/fy22osti/83566.pdf.

Prepared by

NREL

NOTICE

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List of Acronyms

Acronym	Definition
ENPA	Enquêtes Nationales de Production Agricole
FAO	United Nations Food and Agriculture Organization
HTG	Haitian gourde
InSPIRE	Innovative Solar Practices Integrated with Rural Economies and Ecosystems Project
NREL	National Renewable Energy Laboratory
PHARES	Programme Haïtien d'Accès des Communautés Rurales à l'Energie Solaire (Haiti)
PUE	Productive use of energy
PV	Photovoltaic
SAM	System Advisor Model
USD	U.S. dollar
USAID	U.S. Agency for International Development

Executive Summary

With less than 2% of the rural population with access to electricity[1] and almost half the population facing acute hunger,[2] Haiti faces interconnected challenges of energy poverty and food insecurity. One solution to help address energy poverty in Haiti has been the development of distributed solar, particularly solar mini-grids. However, often the land well suited for deploying solar generation is also well suited for agriculture by smallholder farmers, thereby creating a potentially complicated tension between energy access and food security.

To address this tension, solar developers, agricultural specialists, and researchers are jointly examining a novel solution called "agrivoltaics." Agrivoltaics is a shared land-use solution that is rapidly expanding in established solar markets like the United States, Europe, and Asia that pairs solar with agriculture, producing electricity and providing space for crops and animal grazing under and between panels. Despite clear benefits and potential to help support both energy access and food security in mini-grid communities, deployment of agrivoltaic solutions in the mini-grid space has been limited.

As part of the Energy Access Partnership for Haiti with the U.S. Agency for International Development (USAID), the National Renewable Energy Laboratory (NREL) performed an initial feasibility analysis and stakeholder engagement project to evaluate the potential for agrivoltaics in mini-grid contexts in Haiti. The analysis considered typical 100-kW and larger 1-MW mini-grids in towns across Haiti and developed two example agrivoltaic archetypes based on key local inputs, including solar irradiance, production data from the agricultural census, market prices, stakeholder interviews, and existing agrivoltaic research. The two archetypes are:

1. **Crop growing**: Growing crops in between and/or underneath the panel rows of a solar mini-grid. Haiti-relevant crops include potatoes, beans, groundnuts, and chilies for the 100-kW system, and yams, pigeon peas, tomatoes, onion, and garlic for the 1-MW system. The archetype also added on potential productive use of energy (PUE) appliances to support agricultural production activities, including cold storage, grinding, and de-shelling.
2. **Livestock**: Grazing livestock in between and underneath the panel rows of a solar mini-grid. The archetype either integrated chickens (egg production or chick raising) or sheep/cattle (only with elevated configurations) with vegetation underneath the solar array. Cold storage and egg incubation productive use appliances were also modeled.

Based on the potential agrivoltaic archetypes for the sample mini-grid systems, NREL developed a three-pronged approach: (1) leveraging existing research; (2) technical modeling using NREL's System Advisor Model (SAM); and (3) stakeholder engagement through interviews with key players in Haiti, including government officials, development partners, mini-grid developers, and agricultural nongovernmental organizations to identify and distill key high-level considerations for developing agrivoltaics for mini-grids in Haiti:

- **Engineering design**: Four different configurations for photovoltaic (PV) mini-grids were identified that represented baseline mini-grids (standard configuration), as well as configurations with wider-spaced rows and/or elevated panels that offer trade-offs for

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[1] ESMAP (Energy Sector Management Assistance Program). 2023. SDG 7 Tracking Report. https://trackingsdg7.esmap.org/country/haiti.

[2] WFP (World Food Programme). 2023. "Haiti." https://www.wfp.org/countries/haiti.

agricultural production and land use. A shading analysis highlighted effective availability of light beneath and between PV panels for all configurations, which informed crop selection.

- **Mini-grid electricity**: All regions had good potential annual solar generation from mini-grids, ranging between 165–170 MWh, with typical monthly available generation ranging 13 MWh–15 MWh for the 100-kW systems and generation roughly scaled by 10x for the 1-MW system. Electricity production was assumed to support downstream electrification of households and businesses as well as powering PUE from the agrivoltaic archetypes.
- **Land use**: Standard configurations had 27% of land available for crops. Wide-row configurations increased total land area needed for solar by 1.85x, but increased farmable area compared to the baseline by 4.18x, as 65% of the wider-row area was farmable. Elevated configurations increased the total area needed for solar by 1.12x, but this allowed 95% of the land to be farmable. Livestock configurations had 98% of land area available for grazing.
- **Agricultural production**: Annual revenue from on-site agricultural production ranged from $150–$950 for the 100-kW system and $590–$15,000 for the 1-MW system, depending on archetype and configuration. Agricultural revenue potential was strongest for crop and chick production, and higher in configurations with more farmable land available. These configurations, however, came with a trade-off: increasing the total land needed for the project footprint. Low baseline yields for staple crops in Haiti limited overall revenue potential for cropping systems but were included for their impact on local food security and nutrition. Through adoption of formalized agricultural approaches (e.g., access to improved seed varieties, irrigation, systematic approaches) in agrivoltaic systems, baseline crop yields were estimated to improve by 30%, with potential additional benefits from the panel microclimate (e.g., shading for crops).
- **PUE**: PUE can enhance value for agrivoltaics by reducing post-harvest losses and expanding productivity/processing through shelling, grinding, and egg incubation. For the modeled applications, crop growing saw a 53%–54% increase over traditional baseline agriculture, and livestock saw a 1%–400% increase, with chick production as the key opportunity. PUE value can be enhanced further by expanding PUE models to serve the broader community, leveraging incentive electricity rates, and aligning with parallel programs. Integrating centralized PUE models through agrivoltaics can also establish a foundational framework for developing other PUE for communities using mini-grids.
- **Water**: In Haiti, only 11% of farmland is estimated to be irrigated, with the remaining 89% rain-fed.[3] Further, 30%–45% of land area faces very high, high, or moderate drought risk, and 60% of the land area in Haiti is insufficiently resilient to withstand drought events and produce adequate agricultural yields.[4] Irrigation in Haiti has been shown to enable crop diversification, increase yields, and increase stability, which highlights a potential opportunity for agrivoltaic mini-grids to integrate irrigation and expand impact. While irrigation water/energy needs are very context-dependent, an estimated 160–790 kWh annually would be needed for a small pumping solution for the 100-kW system (<1% of total generation). Initial models for irrigation could also be adapted to help support other water pumping opportunities for example for sanitation and drinking water for the broader community.

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[3] USGS (U.S. Geological Survey EROS. 2023. Global Food Security-support Analysis Data Project: Landsat-derived Global Rainfed and Irrigated- Cropland Product @ 30-m (LGRIP30) of the World. https://lpdaac.usgs.gov/documents/1618/LGRIP30_ATBD_v1.pdf.

[4] Elusma, Manassé, Ching-pin Tung, and Chia-Chi Lee. 2022. “Agricultural drought risk assessment in the Caribbean region: The case of Haiti.” *International Journal of Disaster Risk Reduction* 83. https://www.sciencedirect.com/science/article/pii/S2212420922006331?casa_token=in0f5GjivQQAAAAA:xm1ar-vlEjwsj5q9wTDaysZi751Y1SdXT7D0Kh2qIdF4c1mC5R43nGkmqOli6ZALlIANw_PZB7o.

- **Costs**: Agrivoltaic costs will vary depending on specific contexts and desired configuration, and will include integration into mini-grids, materials/supplies, PUE equipment, training, staff time, etc. Specific projects and collaboration are needed to estimate cost ranges for Haiti; however, depending on the application, agrivoltaics is expected to be able to be integrated cost-effectively, especially for the crop archetype and standard mini-grid configuration.
- **Business/collaboration models:** Business models should match the unique context of potential agrivoltaic pilots, but key factors include crop/livestock selection, partnerships with local farming cooperatives, local governance and decision-making, appropriate PUE, alignment with other programming, and training/workforce development opportunities.
- **Capacity building**: Capacity building and training for mini-grid operators and downstream partners will be critical for the success of agrivoltaic pilots, particularly in safety, site access, agrivoltaic operations, PUE, data management, entrepreneurship, etc.
- **Community engagement**: Transparent and early co-development alongside the mini-grid communities is critical for agrivoltaics, and key considerations include: (1) participatory planning; (2) impact assessment; (3) clear roles, responsibilities, and agreements; and (4) information-sharing and communication.
- **Gender**: Agrivoltaics offers several key entry points for gender mainstreaming, including project design, partnerships, agricultural production/processing, markets/distribution, training, workforce development, community engagement, and financial/digital inclusion.

Overall, agrivoltaics can provide clear benefits for local communities by increasing the supply of locally grown crops, expanding access to PUE, and improving income opportunities. These benefits can improve community buy-in, which helps sustain the mini-grid model, especially when coupled with other benefits, including PUE electricity loads, agricultural resilience, and reduced negative impacts for land use (Figure 16).

While this report focuses on the Haiti mini-grid context specifically, many of the findings, approaches, and considerations are relevant to other geographies and solar configurations (e.g., utility-scale). In addition to the general considerations, the initial analysis surfaced five overarching recommendations for advancing agrivoltaic solutions for mini-grids in Haiti:

- **Learn by doing**: Develop a pilot project for agrivoltaics that prioritizes learning (what does not work is as important as what does), tests key assumptions, validates cost assumptions, and identifies key unknowns.
- **Start simple**: First pilots should be deployed without adding significant operational complexity, costs, or implementation risk for developers and their partners. These can provide foundational learnings and frameworks for adding other elements or complexity later.
- **Prioritize co-development and capacity building**: Developers and other partners should identify and involve local cooperatives early on in project scoping/design to enable the co-development of agrivoltaic solutions and systematic training and capacity building.
- **Integrate gender intentionally from the start**: Agrivoltaic projects should incorporate entry points for gender from project design, particularly engaging local women’s groups to support broader mainstreaming (e.g., training, workforce, and agri-entrepreneurship).
- **Enable patient and flexible support**: Pilot projects require patient and flexible timelines, support, and finance from partners to dynamically adapt to changing circumstances in Haiti.

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1 Introduction

Through the U.S. Agency for International Development (USAID)-National Renewable Energy Laboratory (NREL) Energy Access Partnership for Haiti, NREL collaborated with the USAID Haiti Mission to improve energy access, clean energy, and resilience goals in Haiti, particularly through the advancement of the mini-grid sector.

As part of this collaboration, NREL developed an initial feasibility analysis and stakeholder engagement project for adapting agrivoltaic solutions for mini-grids to help support energy access and food security in rural communities in Haiti. In conjunction with the technical aspects, NREL used a detailed stakeholder engagement process to inform and validate findings. The project's overall objective is threefold:

1. Assess the viability of integrating agrivoltaics into mini-grids, balancing the competing needs for energy access, agricultural production, community buy-in, and financial viability
2. Identify clear considerations across a variety of technical aspects, including agricultural suitability, engineering design, business models, and stakeholder engagement to inform stakeholders on how to effectively adapt agrivoltaic solutions to the mini-grid context
3. Develop key recommendations to inform potential pilot projects for agrivoltaics in Haiti.

This report is meant to provide an overview of key considerations for how agrivoltaic solutions can be adapted to the mini-grid context in Haiti. It develops novel analysis assessing different aspects of potential agrivoltaics and mini-grids in Haiti and provides key recommendations for developing potential pilot projects. While the report does develop specific modeling and analysis for "sample mini-grids," it is not meant to be a prescriptive "be-all, end-all" document for agrivoltaics, but is intended instead to inform stakeholders regarding the key considerations for pilot projects. Further, any potential pilot project should be developed and tailored to its specific context and needs, which may not be fully addressed with the modeling presented in this report. The report also mostly focuses on more full-spectrum research/learning pilots, but there could be other applications that are less complex and focus only on the core agricultural components.

Finally, while this report is tailored to the Haiti mini-grid context, many of the findings, approaches, and considerations are relevant to other geographies and solar applications (e.g., utility-scale solar).

2 Background

Introduction
Background
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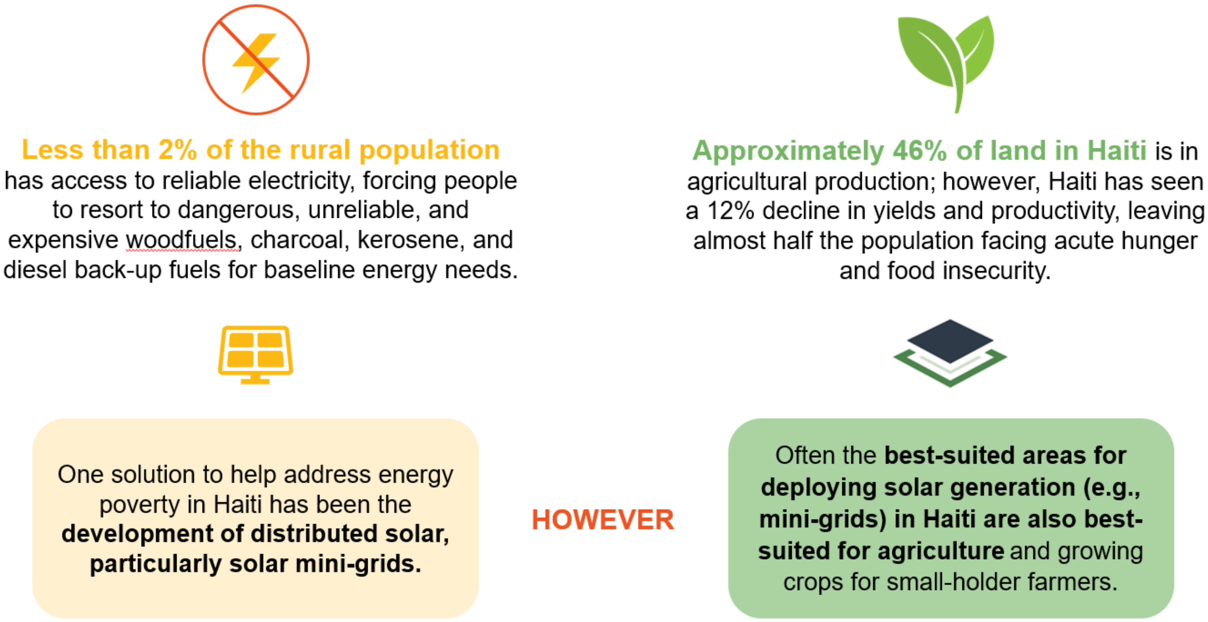
Discussion and Recommendations

With less than 2% of the rural population with access to electricity[5] and almost half the population facing acute hunger,[6] Haiti faces interconnected challenges for energy poverty and food insecurity (Figure 1).



Less than 2% of the rural population has access to reliable electricity, forcing people to resort to dangerous, unreliable, and expensive woodfuels, charcoal, kerosene, and diesel back-up fuels for baseline energy needs.

Approximately 46% of land in Haiti is in agricultural production; however, Haiti has seen a 12% decline in yields and productivity, leaving almost half the population facing acute hunger and food insecurity.

One solution to help address energy poverty in Haiti has been the **development of distributed solar, particularly solar mini-grids.**

HOWEVER

Often the **best-suited areas for deploying solar generation (e.g., mini-grids) in Haiti are also best-suited for agriculture** and growing crops for small-holder farmers.

Figure 1. Haiti's interlinked challenges for energy access and agriculture[7]

On the energy side, Haiti is among the highest energy poverty countries in the world. Without access to electricity, households and businesses rely on harmful and expensive alternatives, particularly wood fuels, charcoal, kerosene, paraffin, battery charging, and diesel gensets. In 2019, over 50% of households spent more than $20/month for these alternatives, despite over 6 million Haitians living below the poverty line with less than $2.41 per day. These costs have risen significantly due to the COVID-19 pandemic and the socio-political situation in Haiti. Haiti's

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[5] ESMAP (Energy Sector Management Assistance Program). 2023. SDG 7 Tracking Report. https://trackingsdg7.esmap.org/country/haiti.

[6] WFP (World Food Programme). 2023. "Haiti." https://www.wfp.org/countries/haiti.

[7] Illustration by Andrew Bilich, NREL

average electricity consumption stood at less than <30 kWh/per capita/year in 2020—more than 80 times lower than the average for the Latin America and the Caribbean region.[8,9,10,11,12]

At the same time, the agricultural sector is also severely constrained. Agriculture is Haiti's largest economic sector, with over 75% of the population relying on rain-fed agriculture for income, yet agriculture only represents 18% of total gross domestic product.[13] Approximately 46% of land in Haiti is in agricultural production; however, high rates of soil degradation and post-harvest losses (35%–50% for some crops) have led to declining yields and productivity (over 12% decline over the past 20 years).[14,15,16,17] Furthermore, farmers lack access to important agricultural inputs, tools, and equipment, such as fertilizers, quality seeds, mechanized equipment, and veterinary products.[18] Availability of digital agricultural tools (e.g., sensors for inputs like soil moisture, phone applications for managing temperature, water, and planting/harvesting, etc.) is also limited, forgoing opportunities to improve agricultural production, efficiency, and distribution.

With this, Haiti does not currently produce enough agricultural products to meet local demand, leading to a strong reliance on imports.[19] The majority of farming in Haiti is subsistence farming, with some surplus available for sales and exports. Estimated crop and livestock production from the 2019 agricultural census in Haiti (Enquêtes Nationales de Production Agricole [ENPA])[20] are included in Figure 2.

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[8] Climate Investment Funds. 2015. SREP Investment Plan for Haiti. https://www.cif.org/sites/default/files/meeting-documents/srep_13_5_srep_investment_plan_for_haiti_0.pdf.

[9] Boston University. 2018. Haiti Electricity Sector Assessment. https://www.bu.edu/igs/files/2018/03/FINAL-Haiti-Electricity-Report-March-2018.pdf.

[10] Belt, Juan A.B., Nicolas Allien, Jay Mackinnon, and Bahman Kashi. 2017. Limestone Analytics Cost Benefit Assessment of the Haiti Power Sector. https://bear.warrington.ufl.edu/centers/purc/docs/papers/1705_CBA_of_Power_Sector_Reform_in_Haiti_2017_10_12(3).pdf.

[11] World Bank. 2017. Haiti Modern Energy Services for All Project. https://documents1.worldbank.org/curated/en/248481507662348381/pdf/Haiti-Modern-PAD-10052017.pdf.

[12] NRECA. 2016. Guides for Electric Cooperative Development and Rural Electrification: Haiti and Dominican Republic Energy Sector Willingness to Pay Assessment. https://www.nrecainternational.coop/wp-content/uploads/2016/11/Module6ConsumerWillingnesstoPayandEconomicBenefitAnalysisofRuralElectrificationProject.pdf.

[13] Strategic Impact Advisors. 2022. Haiti Digital Agriculture Assessment. https://files.digitalfrontiersdai.com/media/documents/Public_Final_Haiti_Digital_Ag_Assessment.pdf.

[14] FAO (Food and Agriculture Organization of the United Nations). 2023. "Haiti." https://www.fao.org/in-action/farmers-organization-africa-caribbean-pacific/country-activities/haiti/en.

[15] WFP (World Food Programme). 2023. "Haiti." https://www.wfp.org/countries/haiti.

[16] IFAD. 2022. "Haiti." https://www.ifad.org/en/web/operations/w/country/haiti.

[17] ICDF (International Cooperation and Development Fund). 2012. Post-Harvest Losses Assessment for Haiti. https://www.icdf.org.tw/public/Data/25189552471.pdf?&mp=mob.

[18] MARNDR. 2023. "Agricultural inputs and tools." https://agriculture.gouv.ht/view/01/?-Intrants-et-outils-agricoles.-

[19] International Trade Administration. 2022. "Haiti Agricultural Sector." https://www.trade.gov/country-commercial-guides/haiti-agricultural-sector.

[20] ENPA. 2019. Résultats des Enquêtes Nationales de Production Agricole. https://agriculture.gouv.ht/statistiques_agricoles/wp-content/uploads/2021/07/Rapport-ENPA-2019_VF-1.pdf.

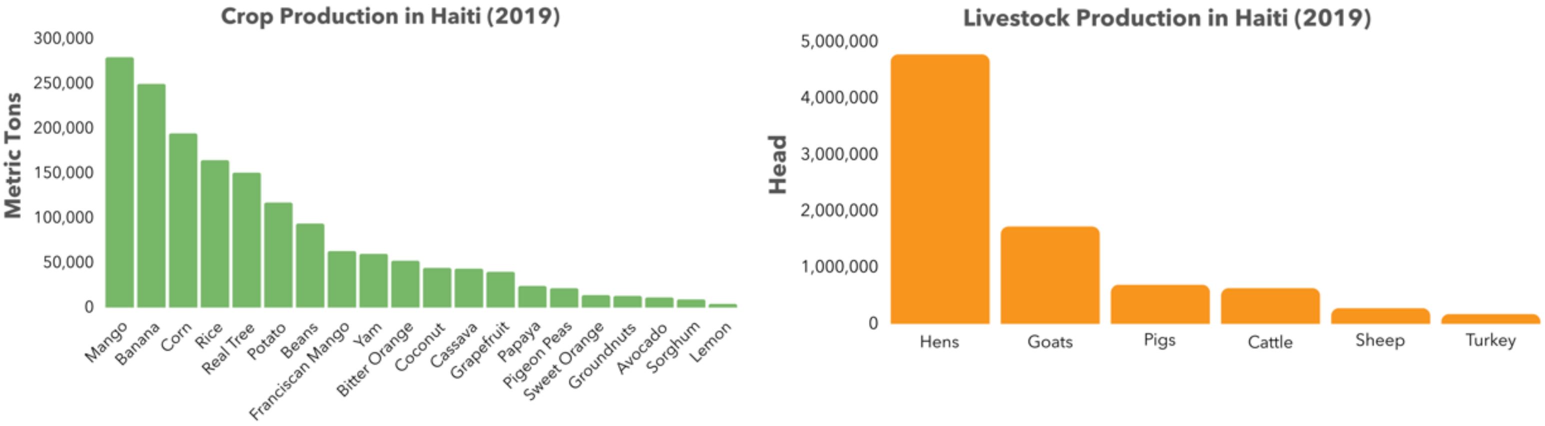

Figure 2. Major crop (left) and livestock (right) production in Haiti[21]

In 2023, Haiti exported $16 million of primary food products, (a 37% decrease from 2009) compared to $618 million of imported food products (a 28% increase from 2009).[22] Haiti's dependence on imports is due to a range of factors, including reduced agricultural production and impacts from natural disasters, domestic and international policies, constrained transportation infrastructure, limited market access, and socio-political instability.[23] Haitian livestock farmers are also facing increasing feed prices, leading to a decrease in production and an increase in meat imports (a 40% increase from 2020 to 2021). A recent rise in inflation of the Haitian Gourde (HTG) has decreased purchasing power for these imports, further reducing access to food. The World Food Programme estimates 30%–77% higher prices for food staples in Haiti compared to the Latin America and Caribbean region.[24] In 2021, 93% of the population was unable to afford a healthy diet, an 8% increase from 2016.[25] In total, over 1.8 million people face emergency levels of hunger, and almost half the population is facing acute hunger and food insecurity. [26]

Energy access has been shown to be a critical enabler of agriculture and food security in rural communities, as it can help power solutions to improve agricultural productivity (e.g., solar water pumping, pest management, climate/weather information, etc.), reduce agricultural loss (e.g., cold storage, drying, early warning systems, etc.), improve value addition and income potential for farmers (e.g., milling, grinding, threshing, hulling, de-kerneling, etc.), and expand market access (e.g., smart phone applications, mobile money), all of which helps support food security.[27,28]

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[21] Illustration by Brittany Staie and Andrew Bilich, NREL

[22] Banque de la République d'Haïti. 2023. "Balance of payments and foreign trade." https://www.brh.ht/statistiques/bdp-et-commerce-exterieur/.

[23] ACAPS. 2023. *Thematic Report: Haiti - A deep dive into the food security crisis.* https://reliefweb.int/report/haiti/acaps-thematic-report-haiti-deep-dive-food-security-crisis-02-august-2023.

[24] WFP (World Food Programme). 2023. "Haiti." https://www.wfp.org/countries/haiti.

[25] FAO. 2023. "Data." https://www.fao.org/faostat/en/#data.

[26] WFP (World Food Programme). 2023. "Haiti." https://www.wfp.org/countries/haiti.

[27] Candelise, Chiara, Donatella Saccone, and Elena Vallino. 2021. "An empirical assessment of the effects of electricity access on food security." *World Development* 141. https://www.sciencedirect.com/science/article/pii/S0305750X21000024.

[28] Zakari, Abdulrasheed, Jurij Toplak, and Luka Martin Tomazic. 2022. "Exploring the Relationship between Energy and Food Security in Africa with Instrumental Variables Analysis." *Energies* 15. https://www.mdpi.com/1996-1073/15/15/5473.

Over the past decade, mini-grids[29] have emerged as a key solution for energy access in Haiti. For example, one of the key planned pathways for energy access is the Haitian Program for Access to Solar Energy for Rural Communities (PHARES, French acronym), which is specifically looking to expand the development of solar mini-grids across the country to support the electrification of rural communities. PHARES is a collaboration between the Ministry of Public Works, Transportation, and Communication Energy Cell (Ministère des Travaux Publics, Transports et Communications Energy Cell), the National Energy Sector Regulator, and the Ministry of the Economy and Finances, with funding support from the World Bank, Inter-American Development Bank, USAID, and others.[30] In its first two requests for proposals, the PHARES program received bids from 7 mini-grid developers to develop mini-grids for 43 towns across Haiti.[31] Development and concessions for those sites are still underway, but construction of new mini-grids is expected over the next few years.

These mini-grids face many challenges, but one critical challenge, especially in Haiti, is access to land. Finding sufficient land that is flat, away from flooding zones, and close to towns for mini-grid development can be a significant hindrance for mini-grid development. At the same time, often the well-suited areas for deploying solar generation are also well suited for agriculture,[32] particularly for smallholder farmers in rural communities. This creates a potentially complicated tension that could hinder energy access and food production in Haiti.

Agrivoltaics is a rapidly expanding solution in established solar markets like the United States, Europe, and Asia that pairs solar with agriculture, producing electricity and providing space for crops and grazing under and between panels thereby balancing energy and food production goals.[33] Agrivoltaics has been shown to increase community acceptance of solar[34] and provide ecological, agricultural, and social benefits, such as increased land-use efficiency, water-use efficiency, income diversification, and job creation, as well as broader sustainable development goals. [35,36]

However, despite clear benefits and enormous potential to support energy access and food security in mini-grid communities, to date, deployment and adaptation of agrivoltaic solutions in the mini-grid space has been limited.

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[29] A mini-grid is a set of small-scale electricity generators (e.g., solar photovoltaics [PV], diesel, etc.) and possibly energy storage systems interconnected to a distribution network that supplies electricity to a small, localized community and operates independently from the national electricity grid. Mini-grids range in a size from a few kilowatts up to 10 megawatts.

[30] ANARSE. "Overview of PHARES Program." https://anarse.gouv.ht/phares/.

[31] ANARSE. 2020. "Proposed and selected localities for the PHARES Program." https://anarse.gouv.ht/wp-content/uploads/2020/09/PROGRAMME-PHARES-Publication-des-localites-proposees-et-selectionnees.pdf.

[32] Adeh, Elnaz, Stephen Good, M. Calaf, and Chad Higgins. 2019. *Solar PV Power Potential is Greatest Over Croplands*. https://doi.org/10.1038/s41598-019-47803-3.

[33] Macknick, Jordan, et al. 2022*. The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study*. https://www.nrel.gov/docs/fy22osti/83566.pdf.

[34] Pascaris, Alexis, Chelsea Schelly, Mark Rouleau, and Joshua Pearce. 2022. *Do agrivoltaics improve public support for solar? A survey on perceptions, preferences, and priorities*. https://doi.org/10.1007/s44173-022-00007-x.

[35] Al Mamun, Mohammed Abdullah, Paul Dargush, David Wadley, Noor Azwa Zulkarnain, and Ammar Abdul Aziz. 2022. "A review of research on agrivoltaic systems." *Renewable and Sustainable Energy Reviews* 161. https://doi.org/10.1016/j.rser.2022.112351.

[36] Walston, Leroy, et al. 2022. "Opportunities for agrivoltaic systems to achieve synergistic food-energy-environmental needs and address sustainability goals." *Frontiers in sustainable food systems.* https://www.osti.gov/pages/biblio/1890118.

3 Methodology

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Given the existing security situation in the country, a rapid desk-based assessment was performed. No in-person or on-the-ground evaluations of specific mini-grid sites were conducted. Instead, the focus of this analysis was a high-level evaluation of key considerations for adapting agrivoltaics to mini-grids in Haiti, evaluating how agrivoltaics projects would broadly interact with mini-grid projects holding everything else constant. To do this, the project team developed "sample mini-grids," and then utilized a three-pronged approach for assessing key gaps, needs, and opportunities for agrivoltaics and mini-grids in Haiti:

1. **Existing data and research**: Desk-based review of existing agrivoltaic research, mini-grids research, as well as publications and data on crop viability, crop productivity, agricultural practices, market prices, PUE, water/irrigation, and mini-grids
2. **Technical modeling**: Techno-economic modeling of potential agrivoltaic and mini-grid configurations
3. **Stakeholder interviews**: Interviews with relevant stakeholders in Haiti to highlight key considerations, needs, and challenges for agrivoltaics.

Based on the map of target mini-grid towns for the first request for proposals of the PHARES program,[37] a few sample towns from departements in the South, Central, and North regions of Haiti were selected to develop composite inputs to inform solar irradiance, crop potential, and other input parameters for the agrivoltaic modeling (Figure 3).

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[37] PHARES. "Map of Target Mini-grid RFP Sites." https://via.illustreets.com/mjdyuSuXw_fsUsMqcBlEN/app/haiti-rfp-20-sites?map=-72.8171*19.3319*8&view=z6otCcjF3.

Figure 3. Sample mini-grid communities for agrivoltaic modeling[38]

To evaluate the potential for agrivoltaics more directly, sample mini-grids were designed to represent "typical" or potential mini-grids in Haiti. First, the analysis considered two sizes of mini-grids, a **100-kW system** and a **1-MW system** for existing mini-grids (e.g., retrofit) vs. new construction of future mini-grids. All mini-grid configurations were assumed to utilize the same panel (e.g., Canadian Solar 400-W monocrystalline[39]) and have a fixed tilt of 18 degrees. Both mini-grid systems also included an energy storage backup (205 kWh for the 100-kW, and 1.845 MWh for the 1-MW system). While diesel gensets are still a common part of mini-grid designs in Haiti, they are not considered in this analysis because of the fuel crisis in Haiti, making costs and supply uncertain to estimate or model. System size remains constant across scenarios.

Further, as the analysis focuses on the "marginal" impact of adding agrivoltaics to a mini-grid model (e.g., all else held constant), the small load added to the mini-grid from the agrivoltaics PUE (see Section 4.6 PUE below) was assumed to be met by solar generation and battery discharging (see Section 4.3 Mini-Grid Electricity below).

NREL's System Advisor Model (SAM),[40] an open-source application for conducting techno-economic analyses of different energy technologies, was utilized to model example mini-grids and estimate mini-grid system sizing and generation across different regions in Haiti. Source code for the SAM modeling is available on GitHub. [41] Modeled energy production used Typical Meteorological Year files from the National Solar Radiation Database, intended to represent typical production; however inter-annual variation can be 10% or more.

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[38] Illustration by Andrew Bilich, NREL

[39] Signature Solar. https://signaturesolar.com/content/documents/CS-Datasheet-HiKu6CS6R-MS-HL_v1.1.pdf.

[40] SAM. https://sam.nrel.gov/.

[41] Model code for the energy techno-economic analysis is available at: https://github.com/NREL/InSPIRE/tree/main/Studies/Haiti_USAID.

SAM was also utilized to conduct shading analysis using the bifacial view factor method.[42,43] A shading analysis was conducted for hourly intervals over the full year for each configuration in each departement to assess the availability of sunlight for crops in different seasons. The outputs from the SAM shading analysis were further processed in the statistical analysis software R[44] to produce daily and monthly mean distributions of light beneath and between PV arrays for the four mini-grid configurations (See Section 4.2 Engineering Design).

PUE appliances were selected based on identified crops and livestock in the agrivoltaic archetypes (see Section 4.1 Agrivoltaic Archetypes below). Expected load profiles were developed based on adapting past hourly load profiles for cold storage, shelling, grinding, milling, egg incubation, and other technologies from PUE studies in Africa.[45,46,47,48] Seasonality for certain crop PUE applications (e.g., shelling and grinding) was developed based on the seasonality for crop production. For example, for the de-shelling, potential PUE load was scaled based on the seasonal production of groundnuts with 100% of full potential load in the spring months, 82% of full potential load in the autumn months, and 78% of full potential load in the winter months (see Section 4.1 Agrivoltaic Archetypes below for modeled equipment and load/utilization assumptions).[49] As alluded to previously, this analysis focused only on the PUE electricity consumption from the addition of the agrivoltaics project and assumed that downstream mini-grid loads for other households and businesses were held constant.

Electricity tariffs for mini-grids in Haiti are an evolving dynamic. The PHARES program has stipulated that the total average tariff across all customers for a mini-grid cannot exceed $0.45/kWh, but developers tend not to charge the same rate for all customers. For example, charging higher rates to high-demand, high-ability-to-pay customers like telecommunications towers can allow developers to offer lower rates to other lower-consumption customers (while still reducing costs for those telecommunications customers compared to baseline diesel gensets). Further, mini-grid developers have already or are starting to shift toward time-of-use rates to account for the very different costs of providing electricity via solar panel production during the daytime hours or batteries/diesel generators at night, especially given the fuel crisis in the country, which has caused diesel fuel prices to increase substantially. Finally, mini-grid developers can also have specialized rates to support business/services development or specific types of customers (e.g., PUE or agrivoltaics).

All of this considered this analysis assumed a rate of $0.45/kWh during nighttime hours (6 p.m.–8 a.m.) and $0.25/kWh during daytime hours (8 a.m.–6 p.m.) for the PUE electricity consumption. It is important to note that most end customers pay in HTG, not U.S. dollars (USD), but the HTG equivalents for tariffs can fluctuate.

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[42] Marion, Bill, Sara MacAlpine, Chris Deline, Amir Asgharzadeh, Fatima Toor, Daniel Riley, Joshua Stein, and Clifford Hansen. "A practical irradiance model for bifacial PV modules." In *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, pp. 1537-1542

[43] Ovaitt, Silvana, Austin Kinzer, Matthew Boyd, James Jones, Chris Deline, and Jordan Macknick. 2023. “Viewfactor and Raytracing for AgriPV Modeling.” https://www.nrel.gov/docs/fy23osti/86631.pdf.

[44] R Core Team. 2021. “R: A language and environment for statistical computing.” https://www.R-project.org/.

[45] Booth, Samuel, et al. 2018. *Productive Use of Energy in African Micro-grids: Technical and Business Considerations*. https://www.nrel.gov/docs/fy18osti/71663.pdf.

[46] Farthing, Amanda, et al. 2023. “Quantifying agricultural productive use of energy load in Sub-Saharan Africa and its impact on microgrid configurations and costs.” https://www.sciencedirect.com/science/article/pii/S0306261923004956.

[47] Avila, Elliot, et al. 2020. *Productive Use of Energy Report*. https://a2ei.org/resources/uploads/2020/09/A2EI_Productive_Use_Report_Agricultural_Technologies.pdf.

[48] BRIHLO. “PEU Market Research for Off-grid Businesses.” https://brilhomoz.com/assets/documents/BRILHO-PEU-Market-research-Off-grid-Business_Final.pdf.

[49] Spring (March–July), autumn (August–November), and winter (December–February) based on ENPA designations.

On the agriculture side, NREL utilized data from existing agrivoltaics and agriculture research in the United States and Europe (e.g., shade tolerance of crops, productivity in agrivoltaic contexts, etc.) cross referenced with crop production data from the most recent agricultural census in Haiti (ENPA 2019)[50]) from the Ministry of Agriculture, Natural Resources, and Rural Development, as well as anecdotal data from the stakeholder interviews (see Section 5 Stakeholder Interviews below) to identify potential crop and livestock suitability for agrivoltaic configurations (additional detail can be seen in Section 4.1 Agrivoltaic Archetypes below). Production potential (kg/ha) of potential crops and livestock (kg/animal) were estimated using data from the United Nations Food and Agriculture Organization (FAO) FAOSTAT database.[51] Other scientific literature was utilized to benchmark and cross reference specific figures for the agricultural and PUE modeling, including productivity, stocking rates, yields, post-harvest losses, and irrigation needs.

Available farmable and grazable land in agrivoltaic systems were calculated based on geometry of different PV spacings with a 20-cm buffer between the edge of the panels and the start of the farming bed. In elevated designs, the 20-cm buffer was removed to allow for more land use. Using panel height and spacing for different configurations, a ground coverage ratio was calculated. Ground coverage ratio is the ratio of the diagonal length of one row of a PV system (viewed from the side) to the space between rows of a PV array. If the ratio is closer to zero, panels are spaced further apart. Using the ground coverage ratio, height, spacing, and panel tilt, total farmable/grazeable area is calculated.

Market values for crops were sourced from the Ministry of Agriculture, Natural Resources, and Rural Development's Agricultural Markets Information System.[52] Each month, the Agricultural Markets Information System produces several weekly bulletins with market prices for key crops for specific markets[53] around the Nippes, Grand-Anse, Centre, and Sud Departements. Average crop prices by season for the identified agrivoltaic crops were constructed using bulletins from the last 10 days of each month in 2023. The Agricultural Markets Information System did not have pricing for livestock products beyond eggs, so indicative pricing was sourced from Farmer Johns, a Haitian agribusiness and butchery that sells livestock products.[54] Stakeholder interviews also helped source general costing figures for specific products, including mamba (Haitian peanut butter usually made with sugar and/or chilies), goats, and chicks.

In Haiti, nearly 50% of all produced fruits and vegetables are lost during post-harvest processes,[,55,56,57] (e.g., processing, storage, transportation, and market) with about 40% of post-harvest losses occurring during on-farm post-harvest and processing processes (i.e., before transportation, retail, and consumption).[58] For this analysis, post-harvest crop losses were modeled at 20% to reflect on-farm and local losses rather than full downstream distribution and

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[50] ENPA. 2019. *Résultats des Enquêtes Nationales de Production Agricole.* https://agriculture.gouv.ht/statistiques_agricoles/wp-content/uploads/2021/07/Rapport-ENPA-2019_VF-1.pdf.

[51] FAO. 2023. "Data." https://www.fao.org/faostat/en/#data.

[52] MARNDR (Ministry of Agriculture, Natural Resources, and Rural Development). "Système d'Information sur les Marchés Agricoles." https://agriculture.gouv.ht/statistiques_agricoles/?cat=47.

[53] Fond des Negres, Thomonde, Paillant, Mirebalais, Les Cayes, Belladere, Abricots, Thomassique, Aquin, Pt. Riv. De Nippes, Beaumont, Corail, Chambellan, Anse d'Hainault, Hinche, Marfranc, Les Irois, Jeremie, Miragoane, Moron, Cavaillon, Thomande, Mirebalais, Les Anglais.

[54] Farmer John's Haiti. https://www.farmerjohnshaiti.com/shop.

[55] Feed the Future. 2017. "Postharvest loss management and food safety research program." https://area.ifas.ufl.edu/projects--partners/postharvest-and-food-safety/.

[56] Quellhorst, Hannah, Anastasia Njoroge, Taisha Venort, and Dieudonne Baributsa. 2020. "Postharvest Management of Grains in Haiti and Gender Roles." *Sustainability*. https://www.mdpi.com/2071-1050/12/11/4608.

[57] Theodat, Romy Reggiani. 2017. *Costs and benefits of interventions to reduce postharvest losses and improve market access*. https://copenhagenconsensus.com/sites/default/files/documents/haiti_priorise_post_harvest_losses_-_english.pdf.

[58] FAO. 2011. *Global Food Losses and Food Waste*. https://www.fao.org/3/i2697e/i2697e.pdf.

transportation chains.[59] Estimates for post-production losses for animal products are less robustly estimated than crop losses, particularly for local markets, so this analysis assumed the same baseline value (20%) for sheep and cattle and leveraged an FAO estimate of 5% average post-production losses in Africa as a proxy for egg losses in Haiti.[60] Chick production was assumed to have 0% on-site post-production loss.

Total revenue for the agricultural production was then estimated by multiplying available land for farming/grazing (see Section 4.4 Land Use) by the potential yield (kg/ha for crops; kg/animal * stocking rate for livestock), adjusting for post-harvest losses (multiplying by 1 minus the post-harvest loss rate), and then multiplying by the market price for the specific product. Revenue figures are reported in both USD and HTG, using a 131.5156 HTG–USD exchange rate.[61]

Given the unknowns of actual project sites and stakeholders, total costs and revenues from the potential agrivoltaic applications analyzed are viewed at the project level (e.g., not allocated to any one stakeholder group), as there can be many partnership or business models envisioned for agrivoltaics (see Section 4.9 Business/Collaboration Models below), and one of the key elements a pilot project should define are which costs and benefits different stakeholders incur. Accordingly, the analysis explored the high-level implications of adding an agrivoltaics pilot project onto a mini-grid (e.g., the total benefits vs. costs) but did not specifically model flows to individual stakeholders. For example, Section 4.5 Agricultural Production and Section 4.6 PUE highlight potential revenue from sales of agricultural production and potential costs of PUE electricity; for this analysis, those values were viewed from the standpoint of a potential agrivoltaics project as a whole, and one of the key elements that a pilot project would need to establish is how those are balanced across stakeholders (e.g., mini-grid developers and local farmers/farming cooperatives).

3.1 Stakeholder Interviews

To capture and highlight valuable stakeholder perspectives, the project team conducted semi-structured virtual interviews from December 2023–January 2024 with key staff from nine organizations active in Haiti, including:

1. Mini-grid developers and solar engineering firms: EarthSpark International, DigitalKap
2. Agricultural and community nongovernmental organizations: HarvestCraft, Fondation Bonne Recolte, Fonkoze Foundation
3. Government institutions: Ministère des Travaux Publics, Transports et Communications
4. Development partners: USAID, Global Energy Alliance for People and Planet, Inter-American Development Bank.

Interview participants were primarily identified through existing networks from the research team. The resulting sample of 15 stakeholders represents experientially and geographically

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[59] 50% estimated total post-harvest crop loss in Haiti x estimated 40% of losses occurring at the farm level = 20% on-farm post-harvest crop losses in Haiti.

[60] Mensah, Evelyn Philomena, Richard Kwasi Bannor, Helena Oppong-Kyeremah, and Samual Kwabena Chaa Kyire. 2021. "An assessment of postharvest losses to support innovation in the egg value chain in Ghana." *African Journal of Science Technology Innovation and Development* 14. https://www.researchgate.net/publication/352005592_An_assessment_of_postharvest_losses_to_support_innovation_in_the_egg_value_chain_in_Ghana.

[61] Banque de la République d'Haïti on February 1, 2024. https://www.brh.ht/.

diverse perspectives and is intended to provide logical (rather than statistical) representation of potential challenges, needs, and opportunities for agrivoltaics in the mini-grid context.

Interview questions differed based on stakeholders' backgrounds; however, core prompts for all stakeholders included questions designed to identify stakeholder perspectives on:

1. Key challenges Haiti faces with respect to energy access, solar development, and agriculture
2. The concept of agrivoltaics in general
3. Proposed agrivoltaic configurations (e.g., crop growing and livestock + supporting PUE applications)
4. Potential barriers, challenges, and opportunities for agrivoltaics
5. Key questions that a pilot project for agrivoltaics in Haiti would need to address.

For mini-grid developers and solar engineering stakeholders, additional questions were asked about technical mini-grid configurations (e.g., panel spacing, panel height) as well as warranties and other operational agreements that could potentially be impacted by an agrivoltaic project. For stakeholders with expertise in agriculture, the interview conversations centered on discussions of current agricultural practices in rural Haiti, including key crops, farm operation norms, and agricultural business models. For development partners, additional questions were asked regarding parallel programming (e.g., PUE, food security, mini-grid, and utility-scale solar investment, etc.) as well as key needs for considering development of a potential pilot project. Finally, for government stakeholders, interviewers asked about regulatory barriers to agrivoltaic integration, particularly related to the PHARES program for mini-grids and existing agricultural initiatives through the Ministry of Agriculture, Natural Resources, and Rural Development.

The stakeholder interviews helped to inform a variety of elements, particularly the agrivoltaic archetypes, key considerations, and recommendations for potential pilots. The stakeholder perspectives are integrated into Section 4 Results and Key Considerations and discussed in more detail in Section 5 Stakeholder Interviews.

4 Results and Key Considerations

Introduction
Background
Methodology
Results and Key Considerations
Stakeholder Interviews
Limitations and Next Steps
Discussion and Recommendations

This section evaluates key results, considerations, needs, and impacts for agrivoltaics across a variety of categories, specifically:

- Agrivoltaic archetypes
- Engineering design
- Mini-grid electricity
- Land use
- Agricultural production
- PUE
- Water
- Costs
- Business/collaboration models
- Capacity building
- Community engagement
- Gender.

These results, considerations, needs, and impacts for agrivoltaics are meant to be indicative and informative based on the initial archetypes (see below) and analysis, but not prescriptive as to what absolutely should be done for future potential pilot projects. To be successful, any potential pilot project will need to be developed and tailored to meet its specific context and needs, and these considerations will necessarily need to be adapted accordingly. Further, these considerations mostly focus on a holistic learning/research pilot, but there could be other applications that are less complex and focus just on the core agricultural components. Finally, while these results are tailored to the Haiti mini-grid context, many of the findings, approaches, and considerations are relevant to other applications, geographies, and contexts for agrivoltaics.

4.1 Agrivoltaic Archetypes

Leveraging the sample mini-grids and three-pronged approach highlighted above, two general archetypes for agrivoltaics—crop growing and livestock—were established (summarized in Table 1 below). These archetypes provide the framework for evaluating key considerations for agrivoltaics for mini-grids in Haiti.

To assess potential crop suitability and selection for the crop archetype, a variety of factors were considered based on key drivers from the broader agrivoltaics literature[62]:

- **Height of plant** and resulting shading/disruption for solar panel electricity generation and access for maintenance
- **Shade tolerance of crops** and potential for productivity in between solar panels
- **Water needs and availability**
- **Local climate and soil conditions**
- **Growing conditions**, particularly if the crop requires special conditions that may disrupt solar production (e.g., flooding for rice[63])
- **Seasonality of production**
- **Import vs. local availability**
- **Necessary agricultural equipment**
- **Market value**
- **End use, markets, and distribution.**

From the crops highlighted in the ENPA census (Figure 2), key crops that are expected to be highly compatible with agrivoltaics and mini-grids are beans, pigeon peas, groundnuts, potatoes, and yams which together represented about 19% of the agricultural production from ENPA in 2019. Additionally, from the stakeholder interviews and the review of market price data from the Agricultural Markets Information System, tomatoes, chilies, okra, carrots, cabbage, spinach, onion, garlic, sweet potatoes, and cassava, are also expected to be compatible with agrivoltaics.

While production occurs year-round for most of the "suitable" crops, there is some seasonality for production across Haiti that should be considered in agrivoltaic configurations. The ENPA,[64] for example, highlighted three key seasons: spring (March–July), autumn (August–November), and winter (December–February). Apart from pigeon peas, which have peak production in the winter, most of the suitable agrivoltaic crops see peak production in the spring (43% of yam production, 48% of bean production, 48% of groundnut production, 65% of potato production, and 10% of pigeon pea production), followed by autumn (27% of yam production, 24% of bean production, 31% of groundnut production, 20% of potato production, and 17% of pigeon pea production). Other crops like tomatoes, chilies, onions, garlic, etc., are similarly expected to produce year-round, but peak in the spring/autumn. While there is some variation across the different geographic regions in Haiti, generally all suitable crops are grown across the whole country.

For the livestock archetype, the ENPA[65] highlighted six key species being produced (Figure 2), and of those, sheep, hens, and turkeys are likely to be compatible under any configuration, and

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[62] Macknick, Jordan, et al. 2022. *The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study*. https://www.nrel.gov/docs/fy22osti/83566.pdf.

[63] Globally, emerging research combines floating solar and specialty configurations to couple agrivoltaics with rice and other crops, but the focus of this project was on more-established approaches, given the complexity of the mini-grid context in Haiti.

[64] ENPA. 2019. *Résultats des Enquêtes Nationales de Production Agricole.* https://agriculture.gouv.ht/statistiques_agricoles/wp-content/uploads/2021/07/Rapport-ENPA-2019_VF-1.pdf,

[65] ENPA. 2019. *Résultats des Enquêtes Nationales de Production Agricole.* https://agriculture.gouv.ht/statistiques_agricoles/wp-content/uploads/2021/07/Rapport-ENPA-2019_VF-1.pdf,

cattle would be compatible in elevated panel configurations (see Section 4.2 Engineering Design below). Goats and pigs tend to create more risk for panel or wire damage so are generally considered to not be compatible with agrivoltaic models.

Based on the selected crops and livestock, PUE applications are also included as potential additions to the base archetypes. This deployment of PUE is meant to be conservative, balancing needs from envisioned crop production with potential impacts on electricity generation and business models (See Sections 4.3 Mini-Grid Electricity and 4.9 Business/Collaboration Models below).

Finally, while there are several potential business and collaboration models for agrivoltaics, for the purposes of this analysis, each archetype was assumed to have a simple collaboration model with a mini-grid developer and a local farming cooperative. All costs and benefits are viewed at the project level.

Table 1. Description of Agrivoltaic Archetypes

Parameter	Archetype #1: Crop Growing	Archetype #2: Livestock
Description	Growing crops in between and/or underneath the panel rows of a solar mini-grid	Grazing livestock in between and underneath the panel rows of a solar mini-grid
Crops/Livestock Selected	The planned crop mix (% of total available area) for the 100-kW crop growing archetype is[66]: • Potatoes (patate ordinaire): 30% • Beans (pois beurre)[67]: 25% • Groundnuts (arachide): 25% • Chilies (piment piqué): 20%. The planned crop mix (% of total available area) for the 1-MW crop growing archetype is: • Potatoes (patate ordinaire): 15% • Yams (igname blanc): 10% • Beans (pois beurre): 15% • Pigeon peas (pois Congo): 10% • Groundnuts (arachide): 10% • Chilies (piment piqué): 10% • Tomatoes (tomate): 10% • Onion (oignon): 10% • Garlic (ail): 10%. Crop mixes were selected to allow for crop diversification for agricultural value as well as to	Chickens: • Average stocking rate[68] = 2,000 chickens/ha. OR Sheep: • Average stocking rate[69]= 40 sheep/ha. OR Cattle (in elevated configurations): • Average stocking rate[70] = 2 cows/ha.

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[66] Given the potentially small plot for crops in the 100-kW standard configuration, only four crops were selected. The potatoes, beans, and groundnuts were selected as staple crops, and the chilies were selected as potential value crops.

[67] Black beans or red beans would also be compatible; butter beans were selected given their prevalence and middle market price.

[68] Stocking rate is the number of animals per hectare. Chicken stocking rate estimated from low density stocking rates of free-range laying hens of chicken behavior and welfare study. Study available at https://pubmed.ncbi.nlm.nih.gov/27821220/.

[69] Stocking rate was estimated from an agrivoltaic sheep production study; 40 was the average stocking rate in the 2020 season. Study available at https://doi.org/10.3389/fsufs.2021.659175.

[70] Stocking rate was estimated using low-density rates from multiyear evaluation of stocking rate and animal genotype on milk production per hectare within intensive pasture-based production systems (2018); available at https://doi.org/10.3168/jds.2017-13632. Effect of Stocking Rate on Pasture Production, Milk Production, and Reproduction of Dairy Cows in Pasture-Based Systems (2008); available at https://doi.org/10.3168/jds.2007-0630 and https://doi.org/10.3168/jds.2017-13632.

Parameter	Archetype #1: Crop Growing	Archetype #2: Livestock
	prioritize learning and data for a potential pilot project.	
PUE	**100-kW system:** 1. Cold storage + grinding/shelling: 2 freezers (90 L, 200 W each) [71], 1 sheller (~100 kg/hr, 500 W); 1 grinder (~50 kg throughput/hr, 1,800 W). [72] **1-MW system:** 1. Cold storage + grinding/shelling: 1 walk-in cold room (~9 tons; 3 kW)[73], 1 Sheller (~800 kg/hr, 3 kW); 1 grinder (~500 kg throughput/hr, 20 kW)[74]	**100-kW system:** Chickens—egg production: 1. Cold storage: 2 freezers (90 L, 200 W each).[75] Chickens—chick raising: 1. Egg incubation: 2 egg incubators (100 eggs each, 100 W).[76] Sheep: 1. Cold storage: 3 freezers (200 L, 360 W). **1-MW system:** Chickens—egg production: 1. Cold storage: 1 walk-in cold room (9 tons, 3 kW).[77] Chickens—chick raising: 1. Egg incubation: 2 egg incubators (500 eggs each, 200 W).[78] Sheep/cattle: 1. Cold storage: 1 walk-in cold room (9 tons, 3,000 kW).[79]
Mini-Grid Configurations Considered	• Standard, wide rows, elevated checkerboard (see Section 4.2 Engineering Design below) • 100-kW/1-MW • Retrofit and new construction.	• Standard, elevated (see Section 4.2 Engineering Design below) • 100-kW/1-MW • Retrofit and new construction.
Potential Changes for 1-MW System	• Addition of walkways for farmer access and mobility.	• Creation of livestock paddocks.

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[71] Assumed to be used 24/7 at 90% of rated capacity draw.

[72] Assumed to be plugged in throughout the day, but more extensively used from 11 a.m. to 2 p.m. with shoulder user from 7–10 a.m. and 3–6 p.m.; load profile developed based on NREL Africa mini-grids and PUE research.

[73] Assumed to be used 24/7 at 90% of rated capacity draw.

[74] Assumed to be plugged in throughout the day, but more extensively used from 11 a.m. to 2 p.m. with shoulder user from 7–10 a.m. and 3–6 p.m.; load profile developed based on NREL Africa mini-grids and PUE research.

[75] Assumed to be used 24/7 at 90% of rated capacity draw.

[76] Assumed to be used 24/7 at 90% of rated capacity draw; load profile developed based on NREL Africa mini-grids and PUE research.

[77] Assumed to be used 24/7 at 90% of rated capacity draw.

[78] Assumed to be used 24/7 at 90% of rated capacity draw; load profile developed based on NREL Africa mini-grids and PUE research.

[79] Assumed to be used 24/7 at 90% of rated capacity draw.

4.2 Engineering Design

Four different mini-grid configurations were considered for the modeling of agrivoltaic solutions, as highlighted in Table 2. The standard configuration represents the baseline mini-grid, while the wide row, elevated, and elevated checkerboard configurations represent options for improving agricultural production. Using these parameters, a ground coverage ratio was calculated which was used to determine shading and land area requirements for PV systems and therefore the available area for crops in an agrivoltaic solution.

Table 2. Mini-Grid Design Configurations

Configuration	Description	Row Spacing (m)	Height (m)	Ground Coverage Ratio
Standard	Represents a baseline mini-grid configuration (based off discussions with stakeholders, as outlined previously)	2.92	0.5	0.62
Wide Row	Increased spacing between solar panel rows to allow for more space for agricultural production and easier access for farmers	5.4	0.5	0.33
Elevated	Elevated panels to allow for grazing cattle and other livestock beneath panels without damage to equipment	2.92	3	0.62
Elevated Checkerboard	Elevated panels with inter-panel spacing to allow for lower shading rates, taller crops, and farmer mobility throughout the field	1.72	2.4	0.95

Each of the configurations was designed to allow for different agrivoltaic archetypes. The standard configuration represents the business-as-usual case for solar mini-grid development in Haiti and will be relevant to retrofit designs. The wide row scenario is more reflective of U.S. solar development practices,[80] and the larger row spacing between panels will allow for more crops to be grown between the panels and better worker access to crops. This scenario will come with a trade-off of greater land use for the same solar capacity as the standard (see Section 4.4 Land Use below). The elevated scenario design is the standard scenario but raised to 3 m off the ground to allow for access for larger grazing animals such as cattle. This height is needed to prevent cattle from damaging panels and equipment. The elevated checkerboard scenario design is a reinforced version of the standard scenario elevated to 2.4 m that will allow for farming to continue underneath the entire panel area. Every other panel in the row is removed to allow for enough light to get through to crops and to mitigate shade (Figure 4).

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[80] Haiti generally has tighter spacing than what is used in the United States.

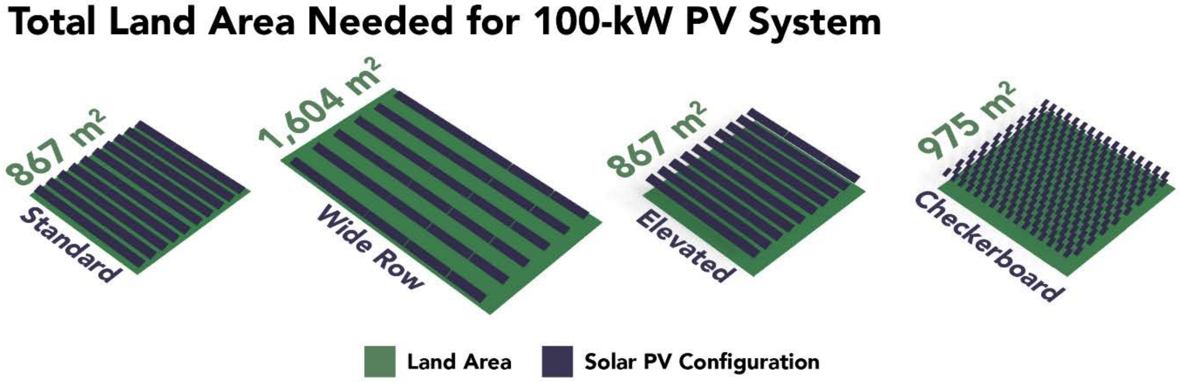

Figure 4. Engineering design for four agrivoltaic configurations[81]

In agrivoltaic systems, the shade introduced by solar panels is a common concern to farmers who depend on sunlight to grow their crops. However, Haiti receives an ample amount of sunlight throughout the year. The total annual amount of sunlight is comparable to southern Arizona, in the United States, where researchers with the NREL InSPIRE project have shown synergistic benefits in agrivoltaic systems, in part due to the ample amount of sunlight.[82] The SAM modeling found relatively consistent patterns of irradiance across the 10 modeled departements. However, more substantial differences in the patterns of light and shade were seen when comparing the four mini-grid configurations (Table 2). For this study, the shading analysis selected the Artibonite region as an example due to its high level of suitable agricultural activity, specifically potato production. Monthly averages of percentage of global horizontal irradiance (GHI) available between and underneath the solar panels (relative to irradiance available above the panels) throughout the year for each configuration is shown in Figure 5.

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[81] Illustration by Thomas Hickey, NREL

[82] Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L., Sutter, L.F., Barnett-Moreno, I., Blackett, D.T., Thompson, M., Dimond, K., Gerlak, A.K., Nabhan, G.P. and Macknick, J.E. 2019. “Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands.” *Nature Sustainability.* https://www.nature.com/articles/s41893-019-0364-5.

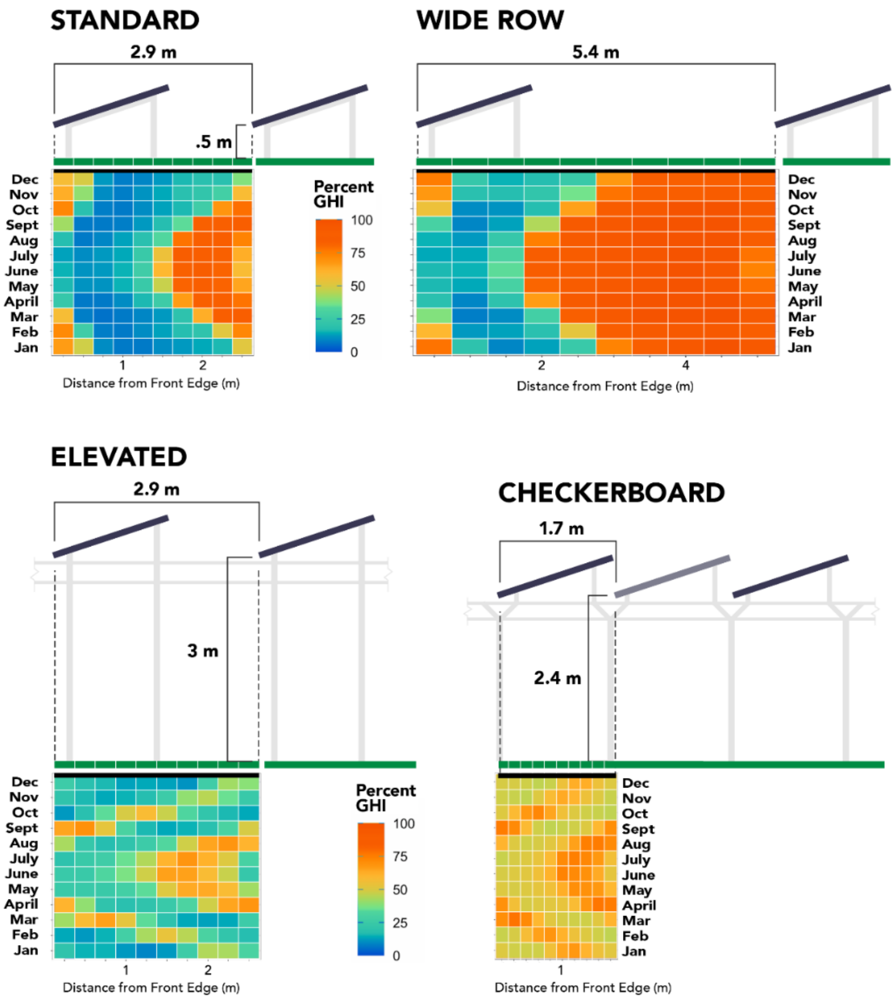

Figure 5. Shading analysis for example mini-grids and agrivoltaic configurations in the Artibonite departement[83]

A final engineering consideration for potential agrivoltaic configurations is safety measures, particularly for placement of equipment and wires. This may include burying underground cabling deeper than normal to allow for tilling and other ground preparation, arranging warning tape in trenches where digging may occur, proper wire management, fencing around electrical equipment, and placing equipment in different areas to allow for access to the farming beds.

4.3 Mini-Grid Electricity

Across the North, Central, and South modeled regions, there was some variability in solar potential and resulting generation from the sample solar mini-grids modeled for the agrivoltaic assessment.

For the 100-kW system, typically available annual solar energy generation was estimated at just over 171 MWh for the North region, 165 MWh for the Central region, and 167 MWh for the South region, for an average of 168 MWh across the whole country. Typical monthly available generation fluctuated slightly, averaging ~14,000 kWh per month overall with minimum

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[83] Illustration by Thomas Hickey, NREL

production averaging ~13,000 kWh in November and maximum production in March averaging ~15,000 kWh. The 1-MW system followed a similar pattern, scaled accordingly. High-level total production estimates can be seen in Figure 6. Production numbers include AC PV generation and battery discharging (AC power that could serve PUE for crops or other end uses). As highlighted previously, diesel generators are not included.

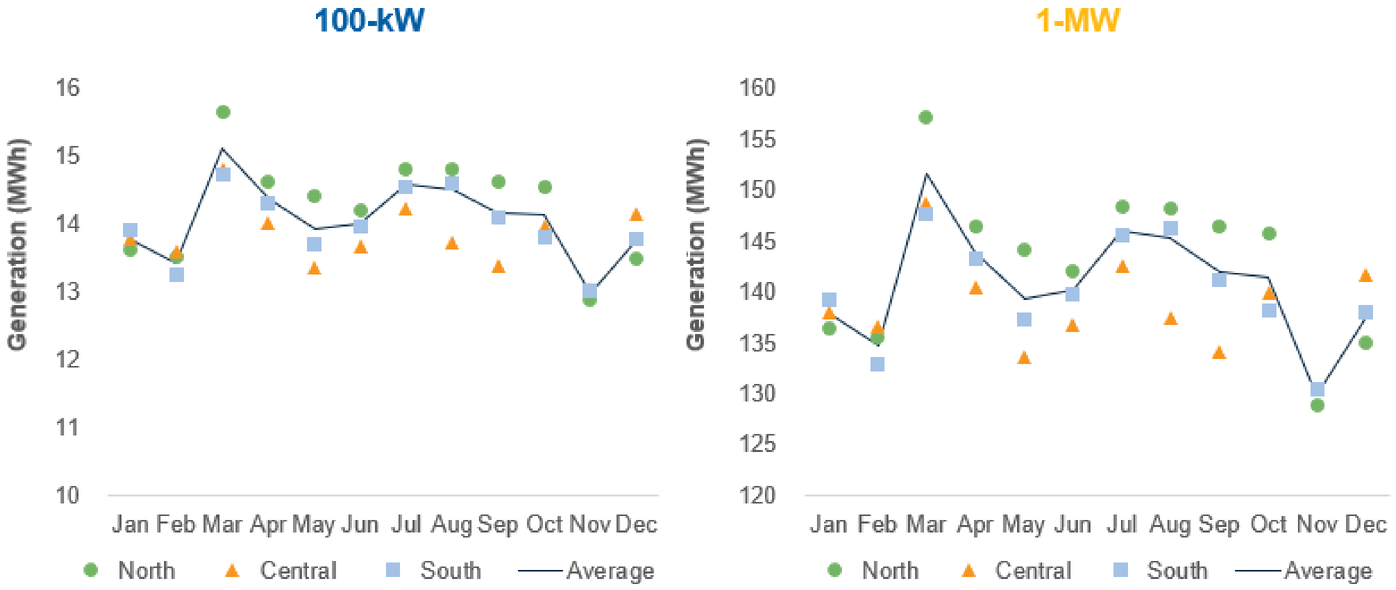

Figure 6. Typical monthly solar production for different mini-grid sizes[84]

4.4 Land Use

Leveraging the characteristics from Table 2, the total area needed for the mini-grid generation sites and the farmable/grazeable area for agrivoltaics were calculated for each of the four configurations and two system sizes (Table 3). Each of the three agrivoltaic crop configurations (standard, wide row, and elevated checkboard) allow for dual use of the land for both energy and agricultural production; however, each design has varied impacts on land usage and agricultural compatibility. All configurations have a total solar capacity of 100-kW or 1-MW, but alternative row and/or panel spacings (for wide row and elevated checkboard configurations) will alter the total amount of land necessary for the solar mini-grid footprint.

Under the standard configuration, the total area needed for the mini-grid generation site was 867 m^2 and 8,672 m^2 for the 100-kW and 1-MW systems, respectively. For the crop archetype, 27% of that land is expected to be farmable for agrivoltaics, leaving only 234 m^2 and 2,341 m^2 of farmable area available, respectively. The wide row configuration will have a larger amount of arable land at the expense of less energy production per hectare. In total, the wide row configuration increases the total area needed by 1.85x to 1,604 m^2 and 16,038 m^2, but allows 61% of the area to be farmable, thereby increasing total farmable area compared to the standard configuration by 4.18x to 978 m^2 and 9,783 m^2. The elevated checkerboard configuration increases the total area needed to 975 m^2 and 9,750 m^2, but allows 95% of the area to be farmable, increasing total farmable area compared to the standard configuration by

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[84] Illustration by Andrew Bilich, NREL

3.95x to 926 m^2 and 9,260 m^2. Elevating solar panels also allows for improved farmer ergonomics and mobility throughout the field and a larger range of compatible crops (e.g., taller and/or more shade-intolerant crops). For the livestock archetype, 98% of the area is expected to be able to be grazed by sheep and chickens in the standard configuration and 98% of the area by cattle in the elevated configuration (Table 3).

To simplify the analysis and combinations of configurations, the crop archetype (and farmable area calculations) was only applied to the standard, wide-row, and checkerboard configurations, and the livestock archetype (and grazeable area calculations) were only applied to the standard and elevated configurations. While the other combinations (e.g., wide row for livestock) are possible, they are less typical and were therefore excluded from the analysis (indicated by a "-" in Table 3). The elevated configuration was only applied for cattle and only in the 1-MW system size, as the 100-kW size does not offer enough total area to support cattle.

Table 3. Total Mini-Grid Area and Farmable/Grazeable Area for Different Agrivoltaic Configurations

Configuration	Farmable Area (%)	Grazeable Area (%)	Total Area 100-kW (m^2)	Farmable Area 100-kW (m^2)	Grazeable Area 100-kW (m^2)	Total Area 1-MW (m^2)	Farmable Area 1-MW (m^2)	Grazeable Area 1-MW (m^2)
Standard	27%	98% (chickens and sheep)	867	234	850	8,672	2,341	8,499
Wide Row	61%	-	1,604	978	-	16,038	9,783	-
Elevated	-	98% (cattle)	867	-	-	8,672	-	8,499
Checkerboard	95%	-	975	926	-	9,750	9,260	-

In Haiti—where availability, suitability, ownership, and costs of land are all critical challenges for land access for mini-grid development—it may be challenging to expand the total generation site footprint to enable some of the non-standard configurations, but there is significant potential for these configurations to help enhance agricultural outcomes and reduce the trade-off between solar development and local agricultural development (see Section 4.5 Agricultural Production below). It should also be noted that some configurations, particularly elevated and elevated checkerboard, may add additional complexity, costs, and implementation risks for mini-grid developers.

4.5 Agricultural Production

4.5.1 Crop Production

With varying land available, the total potential agricultural yield per system will also differ based on the selected agrivoltaic configuration. These yield variances will also then impact annual agricultural revenue potential. Post-harvest food losses, which are factored into baseline revenue potential in Table 4, can also have a significant impact.[85] As highlighted in Section 3 Methodology previously, post-harvest crop losses were modeled at 20% to reflect on-farm and local losses rather than full downstream distribution and transportation chains.[86] Further, the

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[85] Quellhorst, Hannah, Anastasia Njoroge, Taisha Venort, and Dieudonne Baributsa. 2020. "Postharvest Management of Grains in Haiti and Gender Roles." *Sustainability*. https://www.mdpi.com/2071-1050/12/11/4608.

[86] 50% estimated total post-harvest crop loss in Haiti x estimated 40% of losses occurring at the farm level = 20% on-farm post-harvest crop losses.

revenue figures were viewed at a project level, and a pilot project would need to establish agreements determining revenue share. For example, if a mini-grid operator partnered with a local agricultural cooperative to support the actual production, the revenue for the agricultural sales would flow to the cooperative (see Section 4.9 Business/Collaboration Models below).

Table 4. Estimated Baseline Yield and Revenue Potential for Agrivoltaic Crop and Livestock Production[87]

System Size	Configuration	Farmable/Grazeable Area (ha)	Crop/Livestock Mix (% of land area)	Baseline Yield (kg/ha) or (kg/animal)	Market Price ($/kg)	Total Annual Yield (kg)	Total Baseline Revenue With Post-Harvest Losses ($)
CROPS							
100-kW	Standard	0.087	Potatoes (30%) Beans (25%) Groundnuts (25%) Chilies* (20%)	12,697 308 217 4,206	$0.74 $3.36 $3.27 $5.72	112	$150
	Wide Row	0.160				468	$630
	Checkerboard	0.173				443	$600
1-MW	Standard	0.867	Potatoes (15%) Beans (10%) Groundnuts (10%) Chilies* (10%) Yams (10%) Pigeon peas (10%) Tomatoes (10%) Onion (10%) Garlic◊ (10%)	12,697 308 217 4,206 5,130 463 15,317 4,992 26,419	$0.74 $3.36 $3.27 $5.72 $1.20 $2.92 $2.52 $2.60 $3.49	1,785	$3,590
	Wide Row	1.604				7,460	$15,000
	Checkerboard	1.735				7,061	$14,200
LIVESTOCK							
100-kW	Standard	0.087	Egg production	9	$4.44	148	$620
		0.087	Chick production	25†	$2.24†	425†	$950
		0.087	Sheep	20	$3.25Δ	69	$180
1-MW	Standard	0.867	Egg production	9	$4.44	1,476	$6,230
		0.867	Chick production	25†	$2.24	4,249†	$9,500
		0.867	Sheep	20	$3.25Δ	687	$1,780
	Elevated	0.867	Cattle	158	$2.76	269	$590

** Chilies yields for Haiti were unavailable, so yield estimates for "other vegetables" were used as a proxy.*
◊ Garlic yields for Haiti were unavailable, so yield estimates for "green garlic" were used as a proxy.
† Chick production yields are in number of chicks and costs in $/chick.
Δ Market prices for sheep meat were unavailable, so goat meat prices were used as a proxy

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[87] Cost / revenue estimates rounded to nearest $10 for clarity

Utilizing 2022 data from FAOSTAT[88] for open-air agricultural yields in Haiti, potential baseline crop yields for the 100-kW systems were estimated at 112 kg for the standard configuration, 468 kg for wide row, and 443 kg for the elevated checkerboard, with potatoes comprising 80% of the weight, chilies 18%, beans 2%, and groundnuts 1%. Crop revenue contributions were as follows: chilies (60%), potatoes (35%), beans (3%), and groundnuts (2%).

For the 1-MW standard configuration, estimated annual total net crop yield was 1,785 kg, with garlic accounting for 35% of weight, potatoes 25%, tomatoes 20%, yams 7%, onion 7%, chilies 6%, beans and pigeon peas 1%, and groundnuts 0.3%. Crop revenue contributions were as follows: garlic (48%), tomatoes (20%), chilies (13%), onion and potatoes (7%), beans and pigeon peas (1%), and groundnuts (0.4%). The tripling of revenue potential for the wide row configurations and near-tripling for the elevated checkerboard was due to the increased farmable land.

Estimated yields and revenue potential per hectare were higher in the 1-MW systems due to the increased rate of high value versus staple crops (80% staple crops in 100-kW systems versus 55% in 1-MW systems). While staple crop production helps to improve local food security, there is a trade-off of growing mostly low-yielding and low-revenue crops, such as beans and groundnuts, in the 100-kW system. There are, however, opportunities to increase revenue potential for certain staple crops through the addition of downstream value-added products (see Section 4.6 PUE below).

Opportunities exist to improve yields for modeled agrivoltaic crops, especially staple crops, in Haiti. Figure 7 shows current yields in Haiti for modeled agrivoltaic crops compared to average yield estimates across the Caribbean and globally.[89] Haiti has been suffering from declining agricultural productivity for over 20 years, and in 2022, groundnut productivity was 47% higher in the Caribbean and 66% higher in global averages than in Haiti. For beans, Caribbean and global yield estimates were 65% and 150% higher than Haiti, respectively. Yams, another staple crop, yielded 103% more in the Caribbean and 65% more globally than in Haiti. Onion yield in the Caribbean and globally was 93% and 271% higher than in Haiti. Data used to estimate yield for chilies[90] showed 250% more production in the Caribbean compared to Haiti. These large differences illustrate the potential for Haitian crop producers to improve yields while not increasing the amount of land used for production.

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[88] FAO. 2023. “Data.” https://www.fao.org/faostat/en/#data.

[89] FAO. 2023. “Data.” https://www.fao.org/faostat/en/#data.

[90] FAOSTAT data utilized for “other vegetables” category due to lack of chilies yield data.

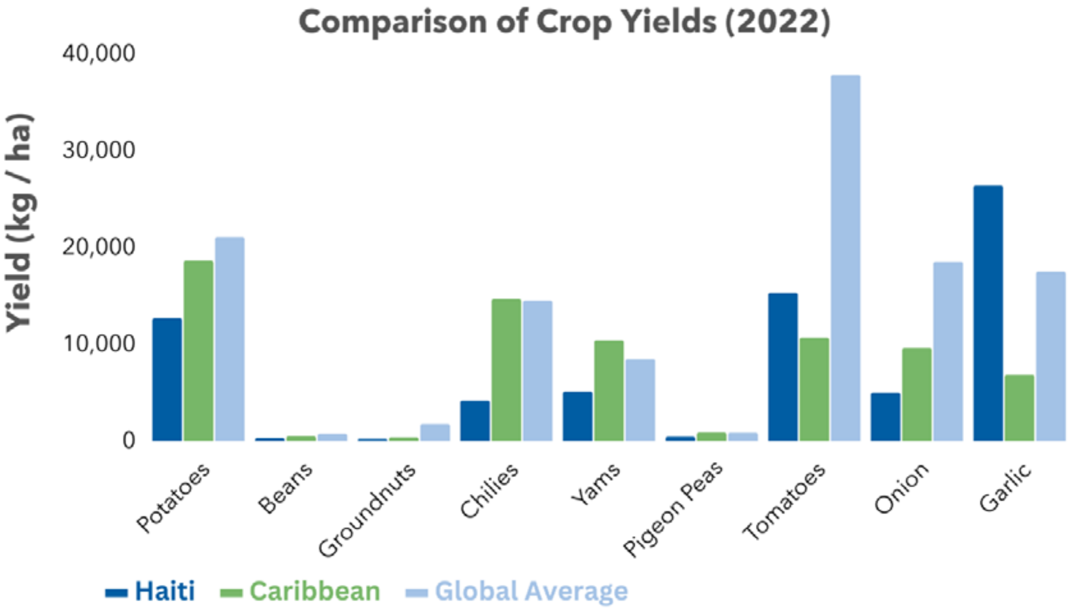

Figure 7. Estimated crop yields for Haiti, the Caribbean, and globally in 2022[91]

An agrivoltaics project could be a catalyst to improve yields by integrating formal processes and improved inputs, such as supplemental irrigation (as discussed in Section 4.7 Water below), higher quality seeds (through integrating research), cultivation of flat land (required for solar installation), and adoption of best agricultural practices (through increasing capacity building). These additions would likely increase crop yields significantly, especially for staple crops. For example, through use of higher-quality seeds, researchers from the Feed the Future Haiti Appui à la Recherche et au Développement Agricole project found bean production could be increased by 70% per hectare in Haiti.[92] Another study found that Haitian groundnut growers could greatly increase yield per hectare through adopting best practices for pest management, watering, planting/harvesting, and in general formalizing agricultural systems.[93] Growing on flat land shows potential to increase peanut production by 27% in Haiti (compared to sloped).[94] Irrigation could also significantly increase yields, but was modeled separately for this analysis (See Section 4.7 Water).

For modeling, this analysis utilized a conservative 30% yield increase to represent the improvement from formalized agricultural systems. Post-harvest losses were again included in both baseline and improved agrivoltaic revenue potentials. Estimated annual crop revenue for improved agrivoltaic production in the 100-kW system was ~$200 (25,909 HTG), ~$820 (155,997 HTG), and ~$780 (102,319 HTG)[95] for the standard, wide row, and elevated checkboard configurations, respectively (Table 6). Section 4.6 PUE below evaluates options for

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[91] Illustration by Brittany Staie and Andrew Bilich, NREL

[92] USAID. 2017. "Road to Improvement for Bean Production Yield in Haiti." https://area.ifas.ufl.edu/media/globalifasufledu/haiti/pdf-stories/Improved-Road-to-Bean-Production-In-Haiti_-ENGLISH.pdf.

[93] Technoserve. 2015. *Smallholder Best Practices Guide: Growing Peanuts in Haiti.* https://ftfpeanutlab.caes.uga.edu/content/dam/caes-subsite/ftf-peanut-lab/documents/pmil/management-entity/Publication_Rhoads_Technoserve_Small_Holder_Best_Practices_Guide_2014_English.pdf.

[94] Kostandini, Genti, James Rhoads, Gregory MacDonald, Eftila Tanellari, Rob Johnson, Eric Connell, and Gael Pressoir. 2021. "Production, post-harvest management and gender dynamics among smallholder peanut farmers in Haiti." *Agriculture and Food Security* 10. https://agricultureandfoodsecurity.biomedcentral.com/articles/10.1186/s40066-021-00311-y.

[95] Assumes a 131.5156 HTG–USD exchange rate; Banque de la République d'Haïti on February 1, 2024. https://www.brh.ht/..

lowering post-harvest losses through incorporating on-site cold storage. As above, these revenue figures are still viewed at a project level.

Table 5. Comparison of Estimated Revenue Potential for Agrivoltaic Crop Production With Post-Harvest Losses and Improved Agricultural Production[96]

System Size	Configuration	Crop/Livestock Mix (% of land area)	Baseline Yield (kg)	Total Annual Revenue After Post-Harvest Loss (USD)	Formalized Agriculture Improved Yield (kg)	Total Formalized Agriculture Improved Revenue With Post-Harvest Loss (USD)
CROPS						
100-kW	Standard	Potatoes (30%) Beans (25%) Groundnuts (25%) Chilies* (20%)	112	$150	145	$200
	Wide Row		468	$630	608	$820
	Checkerboard		443	$600	576	$780
1-MW	Standard	Potatoes (15%) Beans (10%) Groundnuts (10%) Chilies* (10%) Yams (10%) Pigeon peas (10%) Tomatoes (10%) Onion (10%) Garlic** (10%)	1,785	$3,590	2,321	$4,670
	Wide Row		7,460	$15,000	9,698	$19,500
	Checkerboard		7,061	$14,200	9,180	$18,460

For agrivoltaics more broadly, the microclimate created by the solar panels has shown to impact both crop yield and seasonality with varying results based on climate, crop type, and farming practices.[97] Some included crops, such as sweet potatoes and yams, are found to be shade-tolerant and suitable for agrivoltaic production, with others, such as peppers, beans, and onions to be moderately shade-tolerant.[98] While individual studies have shown varying crop yield changes in agrivoltaic settings (increases up to 300% for peppers and 100% for tomatoes[99] to decreases up to 58% for cucumbers and 27% for wheat[100]), on-site empirical data collection is necessary for understanding the impact of agrivoltaics on local crop production (See Section 4.10 Capacity Building below). Due to lack of Haitian agrivoltaic crop production data, impact of agrivoltaic microclimates on yield potentials was not included in this analysis. Future agrivoltaic pilot project(s) in Haiti could help to fill this data gap. Recommended data collection metrics and capacity-building recommendations for future projects are discussed in Section 4.9 Business/Collaboration Models and Section 4.10 Capacity Building.

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[96] Cost / revenue estimates rounded to nearest $10 for clarity

[97] Al Mamun, Mohammed Abdullah, Paul Dargush, David Wadley, Noor Azwa Zulkarnain, and Ammar Abdul Aziz. 2022. "A review of research on agrivoltaic systems." *Renewable and Sustainable Energy Reviews* 161. https://doi.org/10.1016/j.rser.2022.112351.

[98] Al Mamun, Mohammed Abdullah, Paul Dargush, David Wadley, Noor Azwa Zulkarnain, and Ammar Abdul Aziz. 2022. "A review of research on agrivoltaic systems." *Renewable and Sustainable Energy Reviews* 161. https://doi.org/10.1016/j.rser.2022.112351.

[99] Barron-Gafford, Greg A., et al. 2019. "Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands." *Nature Sustainability* 2. https://doi.org/10.1038/s41893-019-0364-5.

[100] Macknick, Jordan, et al. 2022. *The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study*. https://www.nrel.gov/docs/fy22osti/83566.pdf.

4.5.2 Livestock Production

Unlike crop production in traditional height configurations (standard and wide row), livestock production can occur both in between and underneath the panels, using 98% of the land (Table 3). Sheep and chickens can graze in traditional height configurations, while cattle require an elevated system to prevent damage to the panels. Similar to crop production, grassland/pasture production can also be impacted by the shading and microclimate created by the panels. Studies have shown a faster daily height growth of grassland vegetation and better forage quality when compared to open-air production.[101] Further, some studies have shown that livestock prefer the shade of panels to a shade cloth[102] and can have lowered respiration rates and body temperatures than livestock in an open field.[103] For this report, yield improvement opportunities for livestock production were not included due to lack of data, especially in the context of Haitian climates and agricultural systems.

As above, estimates for post-production losses for animal products are less robustly estimated than crop losses, particularly for local markets, so this analysis assumed the same baseline value (20%) for sheep and cattle and leveraged an FAO estimate of 5% average post-production losses in Africa as a proxy for egg losses in Haiti.[104] Chick production was assumed to have 0% on-site post-production loss.

With this, chick production had the highest potential revenue, followed by eggs, then sheep/cattle (Table 4). While chick and egg production generate the highest annual revenue estimates for livestock, these systems tend to be much more labor-intensive than grazing sheep and/or cattle,[105] and these variables should be taken into consideration when evaluating future agrivoltaic projects. Cattle production produced the lowest amount of food (kg) and revenue in the 1-MW system and would likely cost more to develop than other livestock systems due to the elevation of panels. Livestock production revenue can also potentially be increased through the addition of PUE, such as cold storage and egg incubators, as discussed in Section 4.6 PUE.

4.6 PUE

As highlighted previously, the agrivoltaic archetypes modeled a few different applications of PUE. For crop production, cold storage and de-shelling/grinding of groundnuts were modeled based on the initial selected crop mix. For the livestock archetype, egg incubation was modeled for chick raising, and cold storage was modeled for egg production and sheep and cattle raising. The selected PUE was meant to be illustrative of potential opportunities, but not an exhaustive representation (see Section 7 Discussion for broader PUE potential). The selected PUE applications highlighted some key considerations and challenges for PUE in agrivoltaic business

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[101] Loan, Madej, et al. 2022. “One Year of Grassland Vegetation Dynamics in two Sheep-Grazed Agrivoltaic Systems.” *HAL Open Science.* https://solargrazing.org/wp-content/uploads/2023/09/Madej_paper1_HAL_INRAE.pdf.

[102] Maia, Alex Sandro Campos, et al. 2020. “Photovoltaic Panels as Shading Resources for Livestock.” *Journal of Cleaner Production.* https://doi.org/10.1016/j.jclepro.2020.120551.

[103] Sharpe, K.T., B.J. Heins, E.S. Buchanan, and M.H. Reese. 2021. “Evaluation of Solar Photovoltaic Systems to Shade Cows in a Pasture-Based Dairy Herd.” *Journal of Dairy Science.* https://doi.org/10.3168/jds.2020-18821.

[104] Mensah, Evelyn Philomena, Richard Kwasi Bannor, Helena Oppong-Kyeremah, and Samual Kwabena Chaa Kyire. 2021. “An assessment of postharvest losses to support innovation in the egg value chain in Ghana.” *African Journal of Science Technology Innovation and Development* 14. https://www.researchgate.net/publication/352005592_An_assessment_of_postharvest_losses_to_support_innovation_in_the_egg_value_chain_in_Ghana.

[105] U.S. Department of Agriculture. 2020. “Labor costs on specialty crop farms accounted for 3 times as much of their total cash expenses as the average for all U.S. farms.” https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=98569.

models, but overall, collocated PUE equipment is seen as a potentially significant value add for agrivoltaic models.

4.6.1 Impact on Agricultural Yields and Revenue

For crop production across the different agrivoltaic configurations and mini-grid system sizes, the PUE applications had a significant impact on estimated potential crop yields/revenue by reducing post-harvest losses and allowing for secondary processing of groundnuts into higher-value mamba. For livestock production, PUE enhanced revenue by reducing post-harvest losses and enhancing chick productivity through egg incubation. Section 7 Discussion highlights some additional potential PUE streams and considerations not modeled in this study.

As highlighted in Section 4.5 Agricultural Production, post-harvest losses in Haiti were conservatively modeled at 20% for both crops and animal products, except eggs, which were modeled at 5%. To assess a conservative value case for adding cold storage, post-harvest losses after cold storage were decreased to 5%, though some studies have highlighted that cold storage and cold chain can reduce losses to 1%–3%. Post-harvest losses for eggs dropped to 4%, as most of the egg production post-harvest loss is understood to be from breakage rather than spoilage.[106] For mamba production, the analysis assumed that 25% of produced groundnut weight[107] is from the shells and that there is a 2:1 ratio for conversion of groundnuts into mamba. Mamba is assumed to be sold at an indicative price of 800 HTG/kg.[108,109]

For the chick-raising archetype, hatchling production in Haiti has declined significantly from 1980 to 2012.[110] During this period, production went from a 1,000,000 hatchling capacity per month to 558,000, and the ratio of production to capacity declined from 40% to 21%. Integrating egg incubators as a PUE can offer an opportunity to increase production and overall flock numbers throughout Haiti.[111] For egg incubation, existing estimates highlight a range of potential improvements for chick production per chicken from 2x–10x, but the most robust of these estimates from Verasol/CLASP (industry leaders in off-grid solar appliance testing)[112] highlighted a potential for 5x improvement in chick production per chicken, which can dramatically increase baseline revenue potential for the chick-raising archetype.

In total, adding PUE and agrivoltaics enhanced the baseline crop production value by 53%–54%, with most of that value coming from reduced post-harvest losses. Egg incubation increased the revenue in the chick-raising archetype by 400%. Finally, adding cold storage increased sheep/cattle production value by 19% and egg production value by 1% (Table 6).

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[106] Mensah, Evelyn Philomena, Richard Kwasi Bannor, Helena Oppong-Kyeremah, and Samual Kwabena Chaa Kyire. 2021. “An assessment of postharvest losses to support innovation in the egg value chain in Ghana.” *African Journal of Science Technology Innovation and Development* 14. https://www.researchgate.net/publication/352005592_An_assessment_of_postharvest_losses_to_support_innovation_in_the_egg_value_chain_in_Ghana.

[107] Davis, Jack P., and Lisa L. Dean. 2016. “Ch. 11—Peanut Composition, Flavor, and Nutrition.” In *Peanuts.* https://www.sciencedirect.com/science/article/abs/pii/B9781630670382000113.

[108] Mamba is not always sold directly in local markets, but rather to downstream distributors, so the price applied is conservative to show potential. The value chain would need to be developed to fully allow the agrivoltaic operation to capture the revenue from mamba.

[109] Estimate from stakeholder conversations.

[110] Schwartz, Timothy. 2015. *Right to Livelihoods in Haiti: Focus on egg production and rural household livelihood strategies*. https://timothyschwartzhaiti.com/wp-content/uploads/2016/03/REPORT_Right_to_Eggs_3_29_15.pdf.

[111] Booth, Samuel, et al. 2018. *Productive Use of Energy in African Micro-grids: Technical and Business Considerations*. https://www.nrel.gov/docs/fy18osti/71663.pdf.

[112] Verasol. 2022. *VeraSol Rapid Product Assessment: A New Approach to Testing Productive Use Appliances*. https://sun-connect.org/wp-content/uploads/VeraSol-Rapid-Product-Assessment-Egg-Incubator-Beta-Testing-v7.pdf.

Differences in revenue from different configurations were due to total production differences, as highlighted above.

As above, the revenue figures are viewed at a project level, and a pilot project would need to establish agreements and partnerships determining which stakeholders earned the revenue.

Table 6. Impact of PUE on Production and Revenue Potential for Agrivoltaic Configurations[113]

Configuration	Revenue: Baseline (USD)	Revenue: Formalized Agriculture (USD)	Revenue: PUE (USD)	Revenue Increase for PUE Over Baseline (%)	Revenue Increase for PUE Over Formalized Agriculture (%)
100-kW					
CROPS (PUE: Cold Storage + Grinding/Shelling) [114]					
Standard	$150	$200	$230	53%	18%
Wide Row Spacing	$630	$820	$970	53%	18%
Elevated Checkerboard	$600	$780	$920	53%	18%
LIVESTOCK (PUE: Chicks—Egg Incubation; Eggs—Cold Storage**;** Sheep—Cold Storage) [115]					
Standard—Eggs	$620	-	$630	1%	-
Standard—Chicks	$950	-	$4,750	400%	
Standard—Sheep	$180	-	$210	19%	
1-MW					
CROPS (PUE: Cold Storage + Grinding/Shelling)[116]					
Standard	$3,590	$4,670	$5,540	54%	18%
Wide Row Spacing	$15,000	$19,500	$23,140	54%	18%
Elevated Checkerboard	$14,200	$18,460	$21,900	54%	18%
LIVESTOCK (PUE: Chicks—Egg Incubation; Eggs—Cold Storage**;** Sheep/Cattle—Cold Storage) [117]					
Standard—Eggs	$6,230	-	$6,300	1%	-
Standard—Chicks	$9,500	-	$47,510	400%	-

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[113] Cost / revenue estimates rounded to nearest $10 for clarity

[114] 2 freezers (90 L, 200 W each), 1 sheller (~100 kg/hr, 500 W); 1 grinder (~50 kg throughput/hr, 1,800 W).

[115] Egg production--cold storage: 2 freezers (90 L, 200 W each); chick--raising (2 egg incubators [100 eggs each, 100 W]); sheep (cold storage: 3 freezers [200 L, 360 W}).

[116] 1 walk-in cold room (~9 tons; 3 kW), 1 sheller (~800 kg/hr, 3 kW); 1 grinder (~500 kg throughput/hr, 20 kW).

[117] Egg production—cold storage: 1 walk-in cold room (9 tons, 3 kW); chick—raising (2 egg incubators [500 eggs each, 200 W]); sheep/cattle (cold storage: 1 walk-in cold room [9 tons, 3,000 kW]).

Configuration	Revenue: Baseline (USD)	Revenue: Formalized Agriculture (USD)	Revenue: PUE (USD)	Revenue Increase for PUE Over Baseline (%)	Revenue Increase for PUE Over Formalized Agriculture (%)
Standard—Sheep	$1,780	-	$2,120	19%	-
Elevated—Cattle	$590	-	$700	19%	-

4.6.2 PUE Electricity Consumption and Costs

PUE electricity consumption for all archetypes and system sizes is shown in Table 7. The results highlight that potential PUE represents a small, but potentially valuable and reliable, single customer off-taker, but not so significant that it limits the potential for connecting other customers and delivering planned energy access.

As highlighted in the methodology, this analysis assumed a rate of $0.45/kWh during nighttime hours (6 p.m.–8 a.m.) and $0.25/kWh during daytime hours (8 a.m.–6 p.m.). Under this structure, the total annual cost of the electricity was higher in all scenarios except the chick-raising[118] archetype (see rationale below Table 7).

As with the revenue figures, the costs for running the PUE appliances are viewed at a project level, and a pilot project would need to establish agreements on how electricity costs would be split (in addition to what the specific tariffs are). For example, an agricultural cooperative partner operating the PUE could pay the mini-grid operator for electricity use, and/or a mini-grid operator could subsidize part of the electricity costs as part of research and development or innovation financing from a project sponsor (see Section 4.9 Business/Collaboration Models below).

It is important to note that the revenue in Table 7 only represents revenue directly from the production on the generation site. See rationale below for broader PUE value stack.

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[118] It is important to note the potential for increased labor intensity for this archetype.

Table 7. Project-Level PUE Costs and Net Revenue for Agrivoltaic Archetypes[119]

	100-kW			1-MW		
Crops						
Parameter	**Standard**	**Wide Row Spacing**	**Elevated Checkerboard**	**Standard**	**Wide Row Spacing**	**Elevated Checkerboard**
Agrivoltaic Production Revenue (USD)	$230	$970	$920	$5,540	$23,140	$21,900
Annual PUE Consumption (kWh)	9,260	9,260	9,260	84,720	84,720	84,720
Proportion of Total Available Mini-Grid Solar Generation (%)	5.5%	5.5%	5.5%	5.0%	5.0%	5.0%
Daytime/Nighttime PUE Consumption (%)	68%/32%	68%/32%	68%/32%	71%/29%	71%/29%	71%/29%
Electricity Cost (USD)	$2,920	$2,920	$2,920	$26,290	$26,290	$26,290
Avg. Tariff (USD/kWh)	$0.31	$0.31	$0.31	$0.31	$0.31	$0.31
Net Revenue (USD)	**$(2,690)**	**$(1,950)**	**$(2,000)**	**$(20,750)**	**$(3,150)**	**$(4,390)**

	100-kW			1-MW			
Livestock							
Parameter	**Standard—Eggs**	**Standard—Chicks**	**Standard—Sheep**	**Standard—Eggs**	**Standard—Chicks**	**Standard—Sheep**	**Elevated—Cattle**
Agrivoltaic Production Revenue (USD)	$ 630	$ 4,750	$ 210	$ 6,300	$ 47,510	$ 2,120	$ 700
Annual PUE Consumption (kWh)	3,154	1,577	8,515	23,652	3,154	23,652	23,652
Proportion of Total Available Mini-Grid Solar Generation (%)	1.9%	0.9%	5.0%	1.4%	0.2%	1.4%	1.4%
Daytime/Nighttime PUE Consumption (%)	42%/58%	42%/58%	42%/58%	42%/58%	42%/58%	42%/58%	42%/58%
Electricity Cost (USD)	$ 1,160	$ 580	$ 3,130	$ 8,690	$ 1,160	$ 8,690	$ 8,690
Avg. Tariff (USD/kWh)	$ 0.37	$ 0.37	$ 0.37	$ 0.37	$ 0.37	$ 0.37	$ 0.37
Net Revenue (USD)	**$ (530)**	**$ 4,170**	**$ (2,920)**	**$ (2,400)**	**$ 46,350**	**$ (6,570)**	**$ (7,990)**

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[119] Cost / revenue estimates rounded to nearest $10 for clarity

The gap between PUE value for the agrivoltaics alone and electricity costs for some archetypes is seen for a variety of reasons:

1. **Limited production potential and oversized PUE appliances**: The amount of land, especially in the 100-kW scenario, is quite limited, and therefore agricultural production solely from the agrivoltaic site is likely not going to be enough just by itself to cover the costs of PUE. Similarly, even with comparatively small PUE appliances modeled, the appliances have substantially more throughput capacity and are modeled at higher utilization than is supported by just the production from the agrivoltaic site alone. For example, for the 100-kW system, the small sheller for the crop archetype has 100 kg/hr throughput, and the grinder has 50 kg/hr throughput, but the total yield of groundnuts from the agrivoltaic production is only 5.8 kg. Further, this report modeled appliances as plugged in for the full day and in operation every day, which further extended the gap for PUE revenue and electricity costs. In practice, some equipment, like grinders/shellers, can be unplugged in the evenings when not in use, which can help avoid higher nighttime tariff levels, but a “max” use case was modeled to show the edge cases for PUE. This highlights the opportunity and need for agrivoltaic models to consider how PUE deployment can support other agricultural production both from the partner cooperatives/associations working on the agrivoltaic project (e.g., production from the cooperatives’ other farmlands or members) as well as the broader community through potential fee for service models (see Section 4.6.3 PUE Value Stack Beyond Agrivoltaics below).
2. **Crop and livestock selection**: As highlighted previously, the selected crop mix represents a balance of staple and value crops, but different crop allocations could focus on higher-value crops or crops with more downstream PUE potential to justify the costs. For example, while the cold storage can support most of the crops, the sheller and grinder are only used for the groundnuts. If groundnuts only represent a small fraction of production (25%, in this case) there may be less need for the PUE, and it will return less overall value for the agrivoltaic project. This also applies to the sheep/cattle, which only had cold storage applications in this model, but could potentially include appliances like milking machines, milk chillers, cheese making, etc., as highlighted in Section 7 Discussion below.
3. **Other financial value stack:** The baseline modeling also left out other potential elements of the value stack for PUE, particularly available incentive financing in the energy access space, innovation financing, and collaboration with other sectoral programs.
4. **Broader impact of PUE on mini-grid models:** It is also important to highlight the impact and importance of PUE more broadly for mini-grid models themselves. Properly sized and sited PUE can help build larger mini-grid systems capturing economies of scale and help smooth and shape load profiles for the grid, which, when combined, can help lower the levelized cost of electricity for mini-grid service and lower tariffs for downstream customers.[120,121,122]

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[120] Booth, Samuel, et al. 2018. *Productive Use of Energy in African Micro-grids: Technical and Business Considerations*. https://www.nrel.gov/docs/fy18osti/71663.pdf.
[121] Power for All. 2020. “Power For All fact sheet.” https://www.powerforall.org/application/files/9615/9302/4971/FS_Mini-grids_productive_use_of_energy_PUE_in_agriculture3.pdf.
[122] EEP (Energy and Environment Partnership Trust Fund). 2018. *Opportunities and Challenges in the Mini-grid Sector in Africa*. https://eepafrica.org/wp-content/uploads/2019/11/EEP_MiniGrids_Study_DigitalVersion.pdf.

4.6.3 PUE Value Stack Beyond Agrivoltaics

Accordingly, while a lot of these elements are not certain and are dependent on the specific geography, mini-grid developer, funding partner for a pilot project, etc., it is important to show how an agrivoltaic project can be built out to better enhance/justify the PUE value streams. As highlighted previously, some key elements for this include:

- **Energy literacy and energy efficiency**: With constrained capacity in a mini-grid setting, most developers already include energy literacy and outreach on energy efficiency and practices for managing electricity use (e.g., time-of-use rates, plug management, etc.). While not an immediate behavior change, unplugging equipment when not in use to avoid vampiric loads is something that could be built up over time, particularly if the impacts on revenue are shown—for example, through the differential between nighttime and daytime rates. For illustration, in the 100-kW system, if the grinder and sheller equipment were unplugged from 7 p.m.–7 a.m., an estimated $200 (26,303 HTG) could be saved. Depending on crop/animal products harvest times, cold storage could also be unplugged,[123] which could add additional savings.
- **Other production revenue**: If an agrivoltaic project is working with local farmers, cooperatives, or associations, the deployed PUE could also support processing for production outside of the agrivoltaic site. For example, if the cooperative collectively had 2 ha[124] of groundnut fields separate from the 100-kW agrivoltaic site, the estimated baseline production would be an additional 347 kg of groundnuts, which could translate into an additional 130 kg of mamba or an estimated $790 (103,897 HTG[125]).
- **Fee-for-service revenue**: Similarly, it is important to highlight the potential for the PUE equipment to provide processing services to the broader mini-grid community. For example, a fee-for-service model (e.g., for shelling or grinding a kilogram of groundnuts) could be developed to further enhance the revenue opportunity for the agrivoltaic collaboration and expand the potential social impact for the community. This is a common practice for which there is existing agricultural PUE equipment in Haiti. Even at a small fee like 25 HTG/kg for de-shelling and 50 HTG/kg for grinding, 5,000 kg of groundnuts annually from the surrounding local community[126] could turn into an additional $2,380 (313,007 HTG[127]).
- **PUE incentives**: As is common in energy access environments, to stimulate mini-grid development, PUE, and downstream economic growth in local communities, the Government of Haiti and its development partners are exploring potential incentives for productive use of electricity as part of the PHARES program. In addition to connection incentives ($/customer connected) for developers for PUE, the PHARES program is also exploring volumetric incentives ($/kWh) to help further incentivize the development of PUE business models. While specific values are still being determined, a small 5 HTG/kWh (~$0.015/ kWh) incentive would reduce electricity costs for the 100-kW system standard crop archetype by $110 (14,466 HTG[128]).

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[123] For some mini-grids, food vendors only plug in their freezers the night before market day when they bring their harvest into town to sell.

[124] The majority of smallholder farmers in Haiti own very small plots (<0.387 ha), but local farming cooperatives can have hundreds of members, and collectively it is not unreasonable to assume that 2 ha of groundnuts are available within the cooperative.

[125] Assuming a 131.5156 HTG–USD exchange rate; Banque de la République d'Haïti on February 1, 2024. https://www.brh.ht/.

[126] This would include both produced and purchased groundnuts. Total annual groundnut production in Haiti is estimated at over 13 million kg or an average of over 22,700 kg for each of the 571 community sections (smallest administrative unit). Therefore, an estimate of 5,000 kg from the surrounding community is very conservative.

[127] Assumes a 131.5156 HTG–USD exchange rate; Banque de la République d'Haïti on February 1, 2024. https://www.brh.ht/.

[128] Assumes a 131.5156 HTG – USD exchange rate; Banque de la République d'Haïti on February 1, 2024. https://www.brh.ht/.

- **Innovation financing**: Innovation or research financing is likely to be needed, at least initially, to support early demonstration pilots for agrivoltaics and mini-grids to help drive key learning and prove out the technical and economic models (see Section 4.9 Business/Collaboration Models below). Part of the funding for an agrivoltaic pilot could include some financing to allow the mini-grid developer to offer the agrivoltaic electricity for PUE at a discounted price. While the full cost of the electricity for the 100-kW configurations is comparatively small in the scheme of potential pilot funding ($1,160 for eggs, $1,740 for chicks, $2,910 for crops, and $3,130 for sheep), for illustration's sake, a pilot covering 10% of the electricity cost would save the cooperatives $120, $170, $290, and $310, respectively, across the 100-kW archetypes.[129] This is not a long-term solution, but is common practice to help enable early stage learning and refinement of the business model for new innovations, especially in emerging markets.
- **Collaboration with other sectoral programs**: Unfortunately, given the challenges in Haiti, particularly for food insecurity, there are several development partner programs that purchase local agricultural products to utilize for example for local nutrition and school lunch programs (e.g., World Food Programme[130]). Mamba in particular has been utilized as a nutritional supplement across Haiti (e.g., Medika Mamba).[131] At a minimum, partnering with these established programs could secure off-take of agricultural production, thereby minimizing risk for the business model; however, the prices paid to local farmers for the agricultural products by the development partners may also be above market rate.

To illustrate the importance of integrating these other elements into planning and business models for agrivoltaic PUE, the example additional cost savings and revenue highlighted above are applied to the 100-kW standard crop archetype in Figure 8. Even without incentive or innovation financing, the PUE model revenue turns positive by expanding the PUE service to serve the broader community.

This is meant to be indicative of the potential value of PUE beyond just the initial agrivoltaics deployment, but the actual potential optimization of revenue streams for agrivoltaics and how stakeholders share those streams are critical elements that will need to be field tested and validated through specific demonstration pilots.

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[129] Assumes a 131.5156 HTG – USD exchange rate; Banque de la République d'Haïti on February 1, 2024. https://www.brh.ht/.

[130] World Food Programme. 2024. "Haiti: Locally sourced school meals nurture the future of students and farmers." https://www.wfp.org/stories/haiti-locally-sourced-school-meals-nurture-future-students-and-farmers.

[131] Meds & Food For Kids. "Medika Mamba." https://www.mfkhaiti.org/our-products.

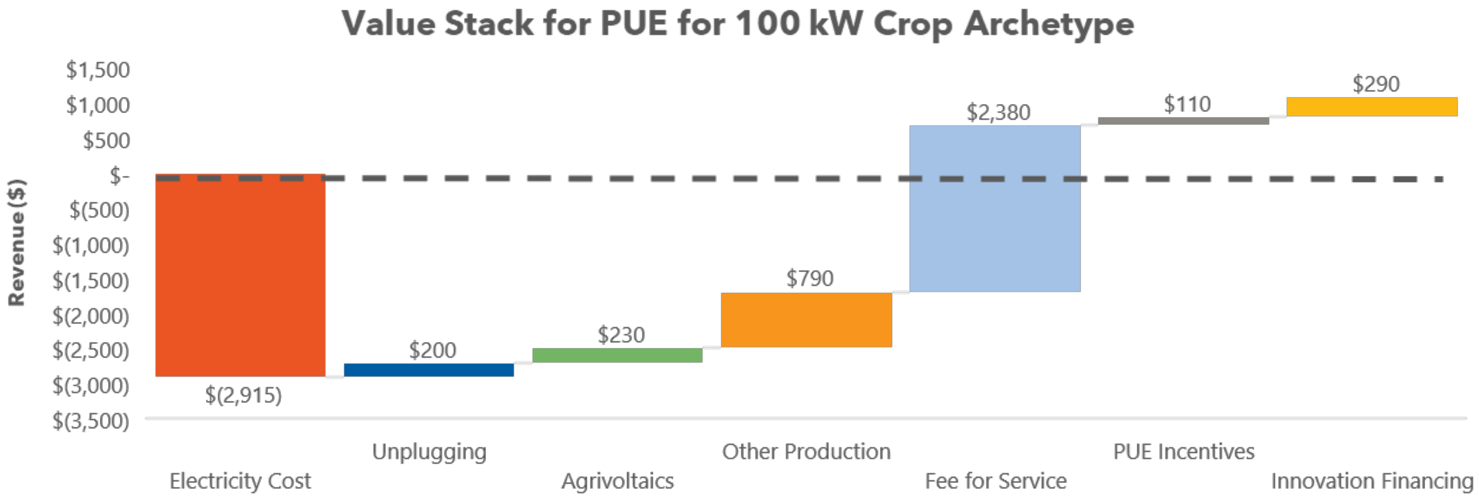

Figure 8. Value stack for PUE for 100-kW crop archetype[132, 133]

The other aspect is the cost of the PUE appliances themselves, which was not directly modeled in this analysis due to the significant uncertainties in cost points for appliances in Haiti, given the security situation and its impacts on logistics, availability of local supply, costs of imports, etc.

The cost of appliances is of course a key element for the PUE business model, and the upfront capital cost for the appliances is likely to be a prohibitive hurdle for some of the local farmers and farming cooperatives. A potential pathway for getting the equipment in place is for the mini-grid developer to instead leverage its better access to finance, logistics, global marketplaces, and information to identify and invest in the equipment, covering the costs directly through pilot or innovation funding (most likely for initial pilots) or establishing a lease-to-own or other type of partnership agreement with the local cooperative who could pay for the equipment over time from the revenue generated from PUE. This approach is likely to work better for specific PUE business models with higher margins and lower costs, for example, egg incubation. Along with upfront appliance costs, it is critical for potential agrivoltaic projects to consider longer-term operations and maintenance of the equipment, including sourcing spare parts to minimize downtime and lost revenue potential. This will be another important facet to explore during initial pilot projects.

4.7 Water

As with any agricultural project, access to water is a critical question that needs to be addressed by potential agrivoltaic pilots. The vast majority of cropland in Haiti is rain-fed, with only 11% of total farmed hectares estimated to be using some form of supplemental irrigation.[134] Haiti does usually receive relatively high rainfall throughout the year (average of 1,502 mm from 1991–2020), but there is seasonal variability, with the most rainfall generally occurring in September–November and the least in December–February. The South region tends to get more rain than the Central or North regions (Figure 9).

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[132] Illustration by Andrew Bilich, NREL

[133] Cost / revenue estimates rounded to nearest $10 for clarity

[134] USGS (U.S. Geological Survey EROS. 2023. Global Food Security-support Analysis Data Project: Landsat-derived Global Rainfed and Irrigated- Cropland Product @ 30-m (LGRIP30) of the World. https://lpdaac.usgs.gov/documents/1618/LGRIP30_ATBD_v1.pdf.

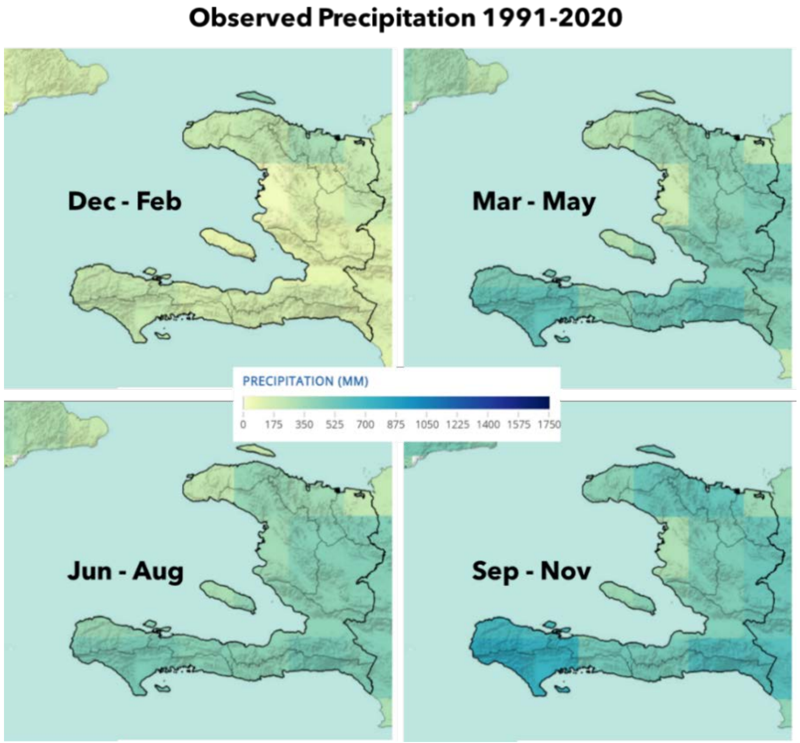

Figure 9. Observed precipitation for Haiti 1991–2020[135]

However, Haiti has been experiencing unseasonably dry and hot conditions over the last decade, particularly the last 5 years, which, coupled with rainfall variability, has led to drought conditions, lower agricultural yields, and impacted livelihoods, especially in the north (Figure 10).[136]

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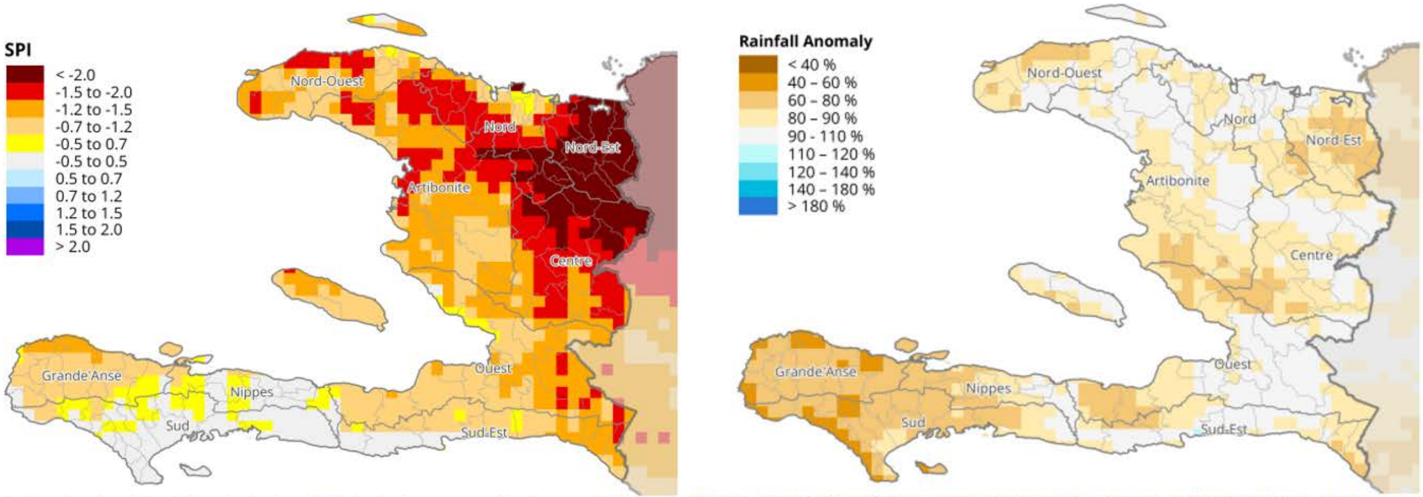
[135] World Bank Climate Knowledge Center. "Haiti." https://climateknowledgeportal.worldbank.org/country/haiti/climate-data-historical.

[136] World Food Programme. 2023. "Haiti: Dry conditions analysis." https://reliefweb.int/report/haiti/haiti-dry-conditions-analysis-march-2023.



Map 1. Standardized Precipitation Index (SPI) in the 3 years ending in Dec 2022

Map 2. 5-month rainfall anomaly (percent of average), ending 20 March 2023

Figure 10. Haiti standard precipitation index (left) and rainfall anomaly (right)[137]

An overall drought risk assessment for Haiti estimates that 10.3%–21.7% of area in Haiti faces high to very high drought risk and 20%–24% faces moderate drought risk, depending on adaptive capacity[138] for the areas. In total, an estimated 60% of the land area in Haiti is insufficiently resilient to withstand drought events and produce adequate agricultural yields (Figure 11).[139]

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[137] World Food Programme. 2023. "Haiti: Dry conditions analysis." https://reliefweb.int/report/haiti/haiti-dry-conditions-analysis-march-2023.

[138] Adaptive capacity is the ability of a system to adjust to take advantage of opportunities or cope with consequences, particularly of climate change. For the drought risk assessment study, adaptive capacity represented measures/conditions to minimize or respond to hazards effects, including distance from river channels, river density, distance to roads, plant available water capacity, etc.

[139] Elusma, Manassé, Ching-pin Tung, and Chia-Chi Lee. 2022. "Agricultural drought risk assessment in the Caribbean region: The case of Haiti." *International Journal of Disaster Risk Reduction* 83. https://www.sciencedirect.com/science/article/pii/S2212420922006331?casa_token=in0f5GjivQQAAAAA:xm1ar-vlEjwsj5q9wTDaysZi751Y1SdXT7D0Kh2qIdF4c1mC5R43nGkmqOli6ZALlIANw_PZB7o.

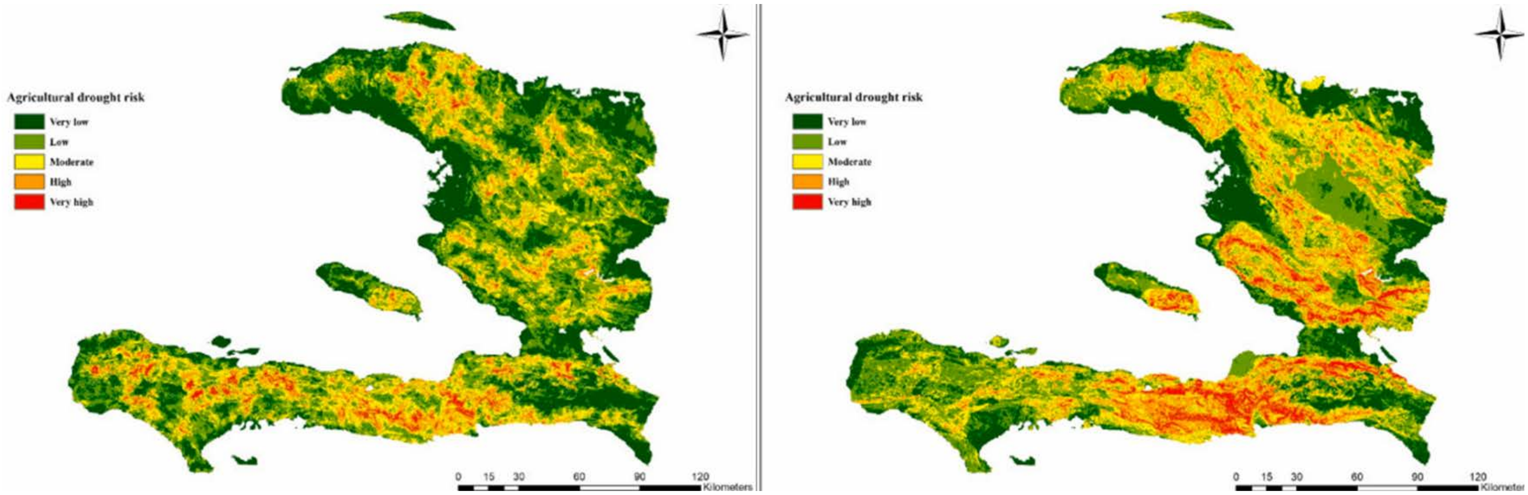

Figure 11. Estimated agricultural drought risk with adaptive capacity (left) and without (right)[140]

This highlights an important need to explore water considerations for agrivoltaic projects, particularly irrigated approaches. Irrigation, while limited in Haiti, has been shown to have outsized impacts for agricultural yields, farmer incomes, land use, and community stability. For example, studies have found a 24%-80% potential yield increase in crop production in Haiti from the addition of supplemental irrigation.[141,142] An Inter-American Development Bank study in Gonaïves highlighted solar irrigation allowing for greater crop diversification, increased revenue generation, and improved social stability.[143]

It is important to note as well that agrivoltaic configurations in general can also have water efficiency benefits. For example, the microclimate created from the solar panels has been shown to reduce soil evaporation[144] and irrigation use,[29] potentially leading to water savings and higher drought tolerance. Further, agrivoltaic livestock production also shows water savings potential for livestock from animals decreasing their daily water intake.[145] Agrivoltaic projects have also implemented rainwater harvesting from panels to bolster local water supplies.[146]

Specific energy and water requirements for irrigation will vary significantly based on factors like the type of crops, soil type, climate, total area, water source and proximity/depth, water quality, type of pumping, mode of application, topography, precipitation, other present water uses, etc. It is therefore critical to tailor any estimate for irrigation and energy needs to the specific potential pilot context.

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[140] Elusma, Manassé, Ching-pin Tung, and Chia-Chi Lee. 2022. "Agricultural drought risk assessment in the Caribbean region: The case of Haiti." *International Journal of Disaster Risk Reduction* 83. https://www.sciencedirect.com/science/article/pii/S2212420922006331?casa_token=in0f5GjivQQAAAAA:xm1ar-vlEjwsj5q9wTDaysZi751Y1SdXT7D0Kh2qIdF4c1mC5R43nGkmqOIi6ZALlIANw_PZB7o.

[141] Mompremier, R., et al. 2021. "Modeling the response of dry bean yield to irrigation water availability controlled by watershed hydrology." *Agricultural Water Management*. https://pdf.usaid.gov/pdf_docs/PA00X5HM.pdf.

[142] Adjognon, Guigonan Serge, Dagbegnon Tossou, and Kathy Baylis. 2023. "The Effects of Irrigation and Weather on Agriculture in Haiti: A Machine Learning Approach." *SSRN*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3893883.

[143] Inter-American Development Bank. 2023. "Empowering Agriculture in Haiti's Artibonite Department with Solar-Powered Irrigation. https://blogs.iadb.org/sostenibilidad/en/empowering-agriculture-in-haitis-artibonite-department-with-solar-powered-irrigation/.

[144] Omer, Altyeb Ali Abakar, et al. 2022. "Water evaporation reduction by the agrivoltaic systems development." *Solar Energy* 247. https://doi.org/10.1016/j.solener.2022.10.022.

[145] Andrew, Alyssa C., et al. 2021. "Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System." *Front. Sustainable Food Sys*. https://doi.org/10.3389/fsufs.2021.659175.

[146] Parkinson, Simon, and Julian Hunt. 2021. "Economic Potential for Rainfed Agrivoltaics in Groundwater-Stressed Regions." *Environ. Sci. Technol. Lett.* Available at https://doi.org/10.1021/acs.estlett.0c00349.

In Haiti, crop-specific water requirements have not been that closely studied, at least recently; however, as a starting point, irrigation water estimates and intervals[147] for different crops were estimated in a 2012 study on irrigated systems in Haiti conducted by Agence Française de Développement.[148] The interval for irrigation depends on the soil type and the evapotranspiration (Table 8).[149]

Table 8. General Irrigation Calendar and Requirements for Selected Crops in Haiti

Crop	Sandy Soil[150]		Silty Soil[151]		Clay Soil[152]	
	Interval (days)	Quantity (mm)	Interval (days)	Quantity (mm)	Interval (days)	Quantity (mm)
Groundnut	3–6	25	4–7	35	6–11	50
Carrots	3–6	25	4–7	35	6–11	50
Beans	3–6	30	4–8	40	5–10	50
Onion	2–3	15	2–4	20	4–7	30
Peppers	3–6	25	4–7	35	6–11	50
Potatoes	3–6	30	4–8	40	5–10	50
Tomatoes	3–6	30	4–8	35	5–10	50

Specific energy requirements for irrigation in Haiti have not been closely tracked (at least not publicly) by the irrigation studies highlighted previously. However, other micro-irrigation studies for mini-grids in Africa can give a general starting point for potential water needs. Across several studies a wide range of energy requirements for irrigation pumping were seen from about 0.04 kWh/m^3–0.7 kWh/m^3 (with most studies ranging between 0.1 kWh/m^3–0.5 kWh/m^3 depending again on total irrigation need, pumping solution, application method, slope, area, geography, water source/depth, etc.).[153,154,155]

This is potentially a meaningful electricity load to add to a mini-grid and to the PUE business model. As an order of magnitude calculation, if, for example, the 100-kW standard crops archetype utilized the irrigation schedule in Table 8 and assumed year-round planting, the max interval for irrigation, and the middle case “silty soil” for irrigation amount, total annual irrigated

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[147] Interval depends on the evapotranspiration and soil type.

[148] Agence Française de Développement. 2012. “Strengthening the skills of irrigators' organizations for the management of irrigated systems in Haiti.” http://innovations-irrigants.iram-fr.org/asirri-haiti/files/classified/module_5_irrigation_gestion_eau_parcelle_avsf_2012.pdf.

[149] Agence Française de Développement project estimated three climates for evapotranspiration (4-5 mm /day, 6-7 mm/day, and 8-9 mm/day).

[150] Water retention capacity is very low, so watering must be at a low dose and more frequent.

[151] Water retention capacity is greater than in sandy or shallow soils. Watering frequency is lower (longer), but the dose is higher.

[152] Retention capacity is highest. Watering frequency should be as low as possible, and watering dose as high as possible.

[153] Ingram, Matthew, et al. 2022. Ethiopia DREAM mini-grids 0.04 kWh/m^3–0.4 kWh/m^3 sourced from *Duke EAP Improving Rural Livelihoods, Energy Access, and Resilience Where It’s Needed Most: The Case for Solar Mini-Grid Irrigation in Ethiopia*. https://energyaccess.duke.edu/wp-content/uploads/2022/07/Improving-Rural-Livelihoods-Energy-Access-Resilience-Where-Needed-Most.pdf.

[154] 0.46 kWh/m^3–0.56 kWh/m^3 Power Africa-Nigeria Power Sector Program mini-grids sourced from *Power Africa Productive Use Solar Irrigation Systems in Nigeria* (2022). https://pdf.usaid.gov/pdf_docs/PA00Z9P4.pdf.

[155] 0.04 kWh/m^3–0.8 kWh/m^3 for mini-grids in Uganda sourced from *The Impact of Climate Change on Crop Production in Uganda—An Integrated Systems Assessment with Water and Energy Implications* (2019). https://www.researchgate.net/publication/335481721_The_Impact_of_Climate_Change_on_Crop_Production_in_Uganda-An_Integrated_Systems_Assessment_with_Water_and_Energy_Implications.

water requirements would be on the order of 1,580 m^3.[156] If the general 0.1-0.4 kWh/m^3 electricity requirements were applied, this would translate to 160–790 kWh ($40-$198 if all daytime load; <1% of the 100-kW system production). It is important to note as well that irrigation pumping can sometimes be a flexible load that can occur when other loads on the mini-grid are lower, which improves the overall utilization and efficiency of the mini-grid. While this amount is meaningful in and of itself, given the tight margins both financially and electrically for a mini-grid agrivoltaics site, it is unlikely that a pumping solution would only service the relatively small area for the agrivoltaics site, but instead would be designed to serve surrounding farm area as well to maximize community benefits and economies of scale for deploying a pumping solution. This means that both water and energy requirements would be substantially higher.

As highlighted above, it is critical that any potential irrigation solution for an agrivoltaics site in Haiti is tailored to the specific context and conditions for that site, as well as community priorities (e.g., for irrigation of surrounding areas).

Finally, as noted previously, the centralized PUE and models from an agrivoltaic project could also provide a foundational framework for broader PUE for communities. For water, this could for example mean and adding water treatment equipment and additional pumping to help address significant challenges for drinking water and sanitation in rural communities in Haiti. For example, in 2022, an estimated 57% of the rural population in Haiti lacked access to basic drinking water, which is a small improvement since 2000 when 59% of the rural population lacked access. For sanitation, most of the rural population (70%) had limited hygiene service and only 15% had basic sanitation.[157]

Full drinking water pumping, treatment, or sanitation applications were not modeled for this study, as the focus was just on the core agrivoltaic models. However, given stakeholder interest in water applications, high-level considerations were evaluated. Basic energy requirements for pumping and treating drinking water in more-established markets are substantial: 0.28 kWh/m^3 for surface water, 0.38 kWh/m^3 for groundwater, and 1.02 kWh/m^3 for brackish water.[158,159,160][161] To contextualize the potential scale of energy requirements, to even meet World Health Organization guidance for basic needs (50–100 liters per person per day[162]) using the figures above, 5–37 kWh would be needed per day, depending on the water source and total amount of water needed, or about 25–185 MWh per year for a small community of 5,000 people.

Given the complexity of potential applications and high potential electricity needs, it will be critical for mini-grid developers to consider these applications from the outset of a mini-grid working directly with the community to scope potential water needs, available space, and costs. This does highlight important potential pathways for aligning with parallel water, sanitation, and

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[156] Peanuts (7-day interval, 35-mm irrigation, 25% of 867 m^2 or 216.8 m^2 = ~396 m^3 annually), beans (8-day interval, 40-mm irrigation, 25% of 867 m^2 or 216.8 m^2= ~396 m^3 annually), peppers (7-day interval, 35-mm irrigation, 20% of 867 m^2 or 173.4 m^2 = ~316 m^3 annually), potatoes (8-day interval, 40-mm irrigation, 30% of 867 m^2 or 260.1 m^2 = ~475 m^3 annually).

[157] Joint Monitoring Programme data. 2022. https://washdata.org/data/household#!/table?geo0=country&geo1=HTI.

[158] Xu, Xuesong, et al. 2022. "Analysis of Brackish Water Desalination for Municipal Uses: Case Studies on Challenges and Opportunities." *ACS EST Engg.* https://pubs.acs.org/doi/10.1021/acsestengg.1c00326.

[159] Giammar, Daniel. E, et al. 2022. "Cost and Energy Metrics for Municipal Water Reuse." *ACS ES&T.* https://pubs.acs.org/doi/pdf/10.1021/acsestengg.1c00351.

[160] EPRI. 2013. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries.* https://www.epri.com/research/products/000000003002001433.

[161] These requirements may be lower in Haiti, and specific energy requirements will be most sensitive to sourcing water (e.g., water depth) and supplying water (e.g., after treatment, how far water must be pumped to households or other centralized locations).

[162] United Nations/World Health Organization. 2015. *The Human Right to Water and Sanitation.* https://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf.

hygiene projects, both by the Government of Haiti as well as by development partners (e.g., World Bank's Decentralized Sustainable and Resilient Rural Water and Sanitation Project in Haiti[163]).

4.8 Costs

Overall capital costs for an agrivoltaic project are going to be highly context-specific and dependent on a variety of factors, including geography, types of archetypes/configurations considered, market conditions, system sizes, retrofit vs. new construction, and developer experience. Given the volatility and uncertainty in the Haitian market, severely constrained logistics and transportation options in-country, and limited in-country materials and equipment, estimating cost information for Haiti is very difficult even when project information is clear (e.g., geography, sizing, configuration, etc.).

For standard configurations, there will likely be minimal cost increases to develop the solar project, but there may be increased costs for managing wires or burying cabling deeper to allow for tilling. There will be operational cost increases to farm that will be the same order of magnitude as normal farming costs. Certain agrivoltaic configurations, particularly wide row and elevated, will likely have an impact on capital costs for a mini-grid project. Increased costs for development will include additional steel to lift and reinforce the panels in elevated configurations, additional wiring for wider configurations, increased land costs (for all but the standard and elevated configuration), increased labor time for installing panels at height (for elevated configurations), and hurricane protection at higher panel levels. Standard configurations, however, could likely be deployed without additional capital costs for the mini-grid itself. One potential cost addition to note for retrofitting systems, even for standard configurations, is existing available power capacity. Integrating PUE for agrivoltaics, for example, may require expansion of solar or battery capacity, which would add to costs.

There are not many current studies on overall development cost for agrivoltaic design scenarios, and those that do exist focus on the U.S. market, not the mini-grid or Haiti context.

While it is not possible to draw specific conclusions on costs of agrivoltaics for Haiti from these studies, they can provide an idea of the order of magnitude for cost impacts in other contexts.

For example, a recent study from NREL comparing the costs of integrating a variety of configurations of agrivoltaics into a 500-kW solar system[164] found that cost adders for similar agrivoltaics configurations ranged from <1% to 52%.[165] While not perfect matches to the archetypes in this analysis, the scenarios from the capital costs study do have similar approaches that can be illustrative for potential cost adders. Mapping the scenarios from the study to the configurations/archetypes identified in this analysis, the below values for capital expenditure adders were estimated:

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[163] World Bank. 2023. *Decentralized Sustainable and Resilient Rural Water and Sanitation Project in Haiti*. https://projects.worldbank.org/en/projects-operations/project-detail/P178188.

[164] Horowitz, Kelsey, et al. 2020. *Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops*. https://www.nrel.gov/docs/fy21osti/77811.pdf.

[165] Full study highlighted a range of $\$0.07/W_{DC}$ to $\$0.80/W_{DC}$ for cost adders, but this extended range includes PV systems with tracking and other applications not considered in this study.

- **Standard (crops)**[166]: minimal cost adders to the typical fixed PV system (maybe <1% for managing wires or burying cabling deeper to allow for tilling)
- **Wider row (crops)**[167]: minimal cost adders to the typical fixed PV system (maybe 2%–3% for additional cabling, managing wires, or burying cabling deeper to allow for tilling)
- **Standard (livestock)**[168]: increase of 4.5%–8% over typical fixed PV systems
- **Elevated checkerboard (crops)**[169]: increase of 44%–50% over typical fixed PV systems
- **Elevated (livestock)**: increase of 52%–60% over typical fixed PV systems.

The capital costs study estimated that the crops archetype could reduce costs for site preparation, site staging, and structural work by almost 30% by reducing line-item costs for several elements, including: clearing and grubbing (-50% costs), soil stripping and stockpiling (-70%), grading (-50%), soil compaction (-80%), and column foundation (-80%). Livestock archetypes can reduce some of these costs as well, but overall end up increasing total costs for site preparation, site staging, and structural work by about 26% given the need for additional grading and column foundations.

Another element of capital costs is land acquisition. Land costs are not usually linearly scaled, especially with scarcity in potential mini-grid communities. However, the 1.85x and 1.12x multipliers for total land need highlighted in Section 4.4 Land Use above are likely a good starting point for estimating additional costs of the nonstandard configurations.

As highlighted throughout, costs in Haiti are likely to be significantly different than the U.S. market, so it is imperative that cost estimates for Haiti are developed and refined through a specific pilot project development process in close collaboration with developers, including quotes from on-the-ground suppliers.

Overall total project costs will vary significantly by archetype and scale, but the key costs to consider and refine in project development include:

- **Project design and stakeholder engagement**: This includes initial project design and development (including costing) as well as initial stakeholder surveying and engagement. It will vary depending on the experience of the project developer and their contextual understanding of potential project areas.
- **Agrivoltaic integration and setup**: This includes the setup of the agrivoltaic site, including land transformation (e.g., tilling), setting up data collection and systems, setting up and integrating PUE, developing site protocols, etc. Standard configurations are likely to have lower costs than other configurations, but these costs will also depend heavily on the site, experience of developer, and existing systems/processes.
- **Agrivoltaic supplies and materials**: Outside the costs for the mini-grid integration itself, there will be important materials and supplies to also procure to support the agrivoltaic projects. The specific bill of materials and supplies needed will be contingent on the ultimate type and configuration of agrivoltaic solutions; however, some general key materials and supplies for a 100-kW agrivoltaic project are highlighted in Table 9. A 1-MW system may consider adding additional fencing for grazing livestock and more robust crop beds. A lot of

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[166] Maps to the “typical fixed PV” scenario in the Capital Costs study ($1.53/W).
[167] Maps to the “typical fixed PV” scenario in the Capital Costs study ($1.53/W).
[168] Maps to the “fixed grazing” scenario in the Capital Costs study ($1.6/W).
[169] Maps to a combination of reinforced elevated and stilt tracker scenarios ($2.21/W) (tracker removed from the balance of system).

these materials are likely to be available in-country, but if not, mini-grid developers will need to coordinate procurement alongside their existing logistics and supply chains.

Table 9. Overview of Key Materials and Supplies for Agrivoltaics

Note: (*Italicized and grey* indicates materials and supplies that are important to productive farming but not part of the baseline required products for agrivoltaic production and research.)

Category	Crops	Livestock
Agricultural Inputs	Seeds, *fertilizer, pest control*	Pasture seed mix, veterinary products, *supplemental animal feed*
Water/Irrigation	*Water access, irrigation pump, irrigation piping/fittings, drip tape*	Water access, water trough, *Irrigation pump, Irrigation piping/fittings*
Agricultural Tools/Equipment	Shovels, axes, machetes, hoes, sheers, harvest bins/buckets, *hand seeder, coolers*	Electric fence[170], *barn/coup*
Measurement and Data Collection tools[171]	Tablets for data entry, data collection software, scales, tape measure, flags/stakes, *printable labels for crops*	Tablets for data entry, data collection software, animal ID system
Personal Protective Equipment[172]	Safety glasses, gloves	Safety glasses
PUE	PUE appliances and spare parts	PUE appliances and spare parts

- **PUE equipment**: Section 4.6 PUE and Section 4.7 Water above also highlight other key costs to consider including the cost of PUE equipment, irrigation/water pumping equipment, potential incentive support for electricity costs to help prove out the business models, and the cost of long-term operations and maintenance and spare parts. Specific costs will depend on equipment procured. Some equipment like cold storage is likely to be more available in-country, but more specialized PUE equipment like grinders, egg incubators, irrigation pumping, etc., may need to be imported.
- **Logistics, customs, and transportation**: This will depend heavily on the security situation and availability of materials in-country but can be a significant adder for both time and costs.
- **Training/capacity building**: This includes development of training materials (pictographic and in Haitian Creole), train-the-trainer workshops, and ongoing supervised learning and training for downstream partners.
- **Grant to support local partners**: This is critically important for building partnerships with local cooperatives. Even a small amount of funding can help build trust and engagement.

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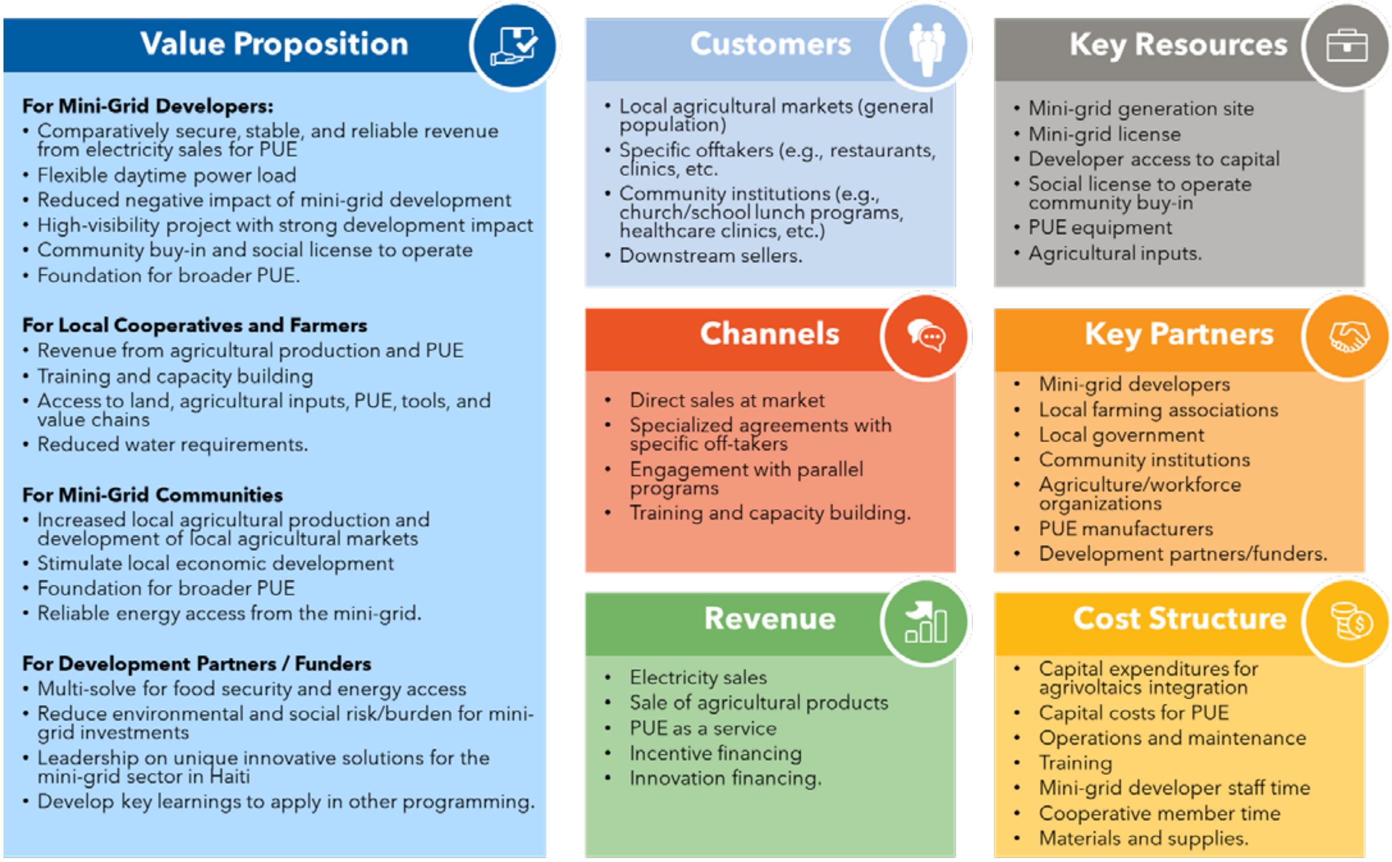
[170] Needed if rotational grazing of livestock is incorporated and/or to assist with predation prevention.
[171] Required for agrivoltaic research sites but not for all agrivoltaic sites in general.
[172] Some agrivoltaic sites may require the additional use of hard hats and high-visibility vests.

- **Technical assistance for agrivoltaics**: This will depend on the capacity and experience of the developer, but it is likely that developers will want support for initial agrivoltaic projects, particularly for project design and setup, planting/harvesting, technical training, data, etc.
- **Staff time**: Staff time costs will depend heavily on local labor rates for the mini-grid operator as well as rates for the developer. Mini-grid developers or other project partners will also likely need to expand local staff capacity to provide needed oversight and management of an agrivoltaic project, particularly during early research phases while training is underway and the operations, collaboration, and business models are being developed.
- **Electricity incentives**: As highlighted in Section 4.6 PUE above, this is not fully needed, but can be helpful to allow for focus on project learning and testing of assumptions, at least for the initial year of operation as the model is proven out.

Finally, it is also important to note that these elements can be ramped up or down depending on the goals of a pilot (e.g., research vs. simplified).

4.9 Business/Collaboration Models

Stakeholders regard the business model as potentially the most complex yet most important aspect of agrivoltaic development. Business and collaboration models for agrivoltaics are both simple in their concept (growing crops or raising livestock alongside solar PV generation) and complex in their design and implementation. Specific business models will need to be developed and refined to match the unique context of potential operating environments, factoring in elements like geography, archetypes, system size, partnerships, funding/partner type, capacity, configuration, PUE, land availability, etc. However, a high-level overview of potential elements of an agrivoltaic business model are summarized below and in Figure 12. Importantly, this is for a full agrivoltaics learning/research model, but some elements may be scaled back depending on the focus.



Value Proposition

For Mini-Grid Developers:

- Comparatively secure, stable, and reliable revenue from electricity sales for PUE
- Flexible daytime power load
- Reduced negative impact of mini-grid development
- High-visibility project with strong development impact
- Community buy-in and social license to operate
- Foundation for broader PUE.

For Local Cooperatives and Farmers

- Revenue from agricultural production and PUE
- Training and capacity building
- Access to land, agricultural inputs, PUE, tools, and value chains
- Reduced water requirements.

For Mini-Grid Communities

- Increased local agricultural production and development of local agricultural markets
- Stimulate local economic development
- Foundation for broader PUE
- Reliable energy access from the mini-grid.

For Development Partners / Funders

- Multi-solve for food security and energy access
- Reduce environmental and social risk/burden for mini-grid investments
- Leadership on unique innovative solutions for the mini-grid sector in Haiti
- Develop key learnings to apply in other programming.

Customers

- Local agricultural markets (general population)
- Specific offtakers (e.g., restaurants, clinics, etc.
- Community institutions (e.g., church/school lunch programs, healthcare clinics, etc.)
- Downstream sellers.

Key Resources

- Mini-grid generation site
- Mini-grid license
- Developer access to capital
- Social license to operate community buy-in
- PUE equipment
- Agricultural inputs.

Channels

- Direct sales at market
- Specialized agreements with specific off-takers
- Engagement with parallel programs
- Training and capacity building.

Key Partners

- Mini-grid developers
- Local farming associations
- Local government
- Community institutions
- Agriculture/workforce organizations
- PUE manufacturers
- Development partners/funders.

Revenue

- Electricity sales
- Sale of agricultural products
- PUE as a service
- Incentive financing
- Innovation financing.

Cost Structure

- Capital expenditures for agrivoltaics integration
- Capital costs for PUE
- Operations and maintenance
- Training
- Mini-grid developer staff time
- Cooperative member time
- Materials and supplies.

Figure 12. Elements of an agrivoltaic business model[173]

A critical enabling factor for the agrivoltaic business model that was consistently highlighted by stakeholders and throughout the mini-grid modeling and agrivoltaic analysis was the need for a strong local partnership, either directly with local farming cooperatives and/or associations that are prevalent across Haiti or indirectly via a community-trusted nongovernmental organization that works directly with the stakeholder farming groups. In the context of Haiti, funding partners will need to be patient and flexible in their approaches to agrivoltaic project implementation, as there is no existing blueprint for agrivoltaic implementation in Haiti to date. Pilot projects are essential to validating best practice approaches to agrivoltaic business model formats in the Haiti-specific context. Partners should be able to iterate upon initial models to strategically guide the project and maintain support amidst the dynamic and challenging operating environment in Haiti. A key consideration is how to split revenue and costs of an agrivoltaics project equitably amongst stakeholder groups.

Potential partnership models will also need to be tailored to the individual agrivoltaic contexts, but a high-level example can be seen in Figure 13. This example is meant to be indicative and capture some of the elements discussed above; however, given the high-level scope of this report, it was not possible to do field validation and refinement of potential business/collaboration models. It is therefore critical for future pilots to first work directly with local developers, cooperatives, and associations to understand baseline operational models and how agrivoltaics can best be integrated.

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[173] Illustration by Andrew Bilich, NREL

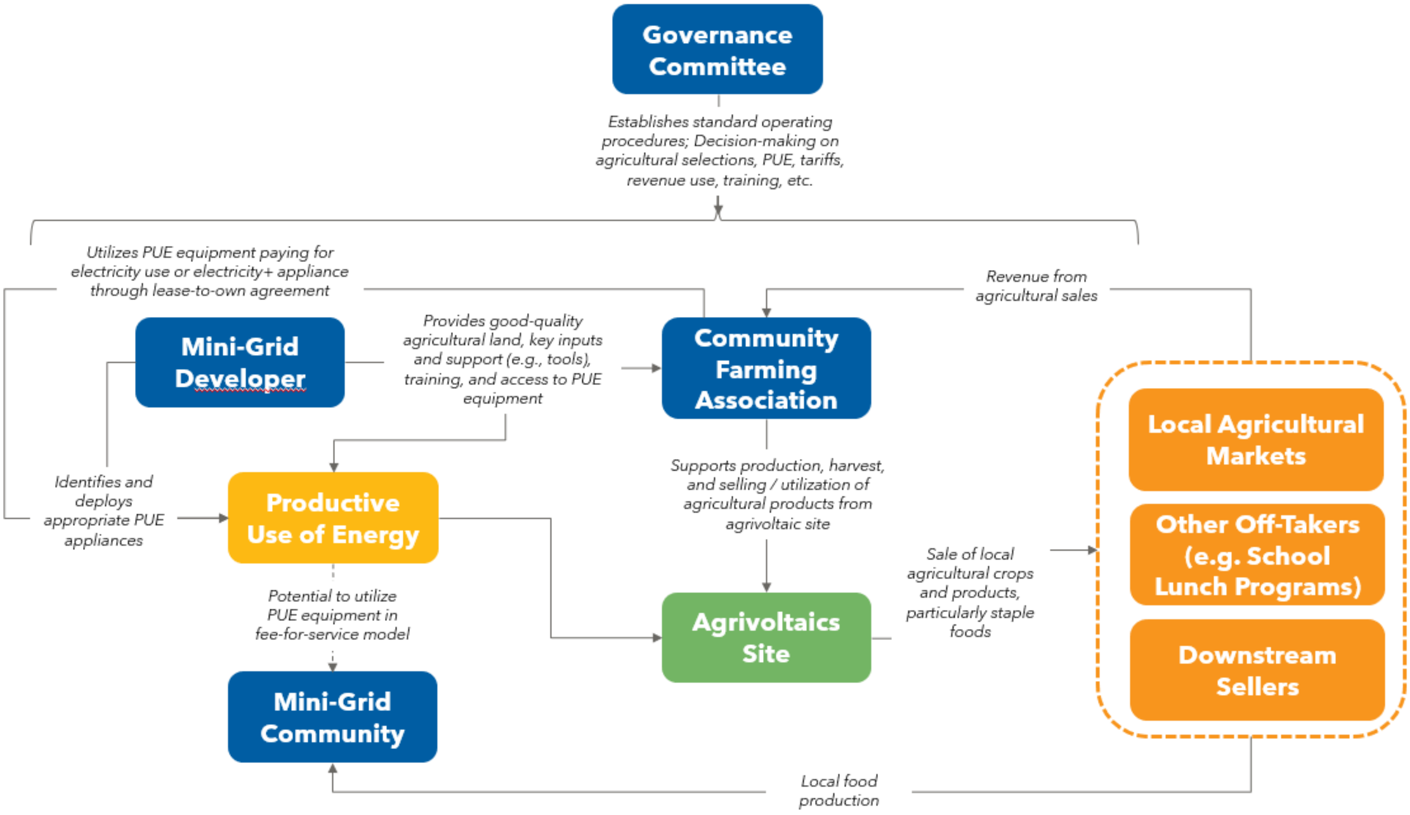

Figure 13. Example agrivoltaic partnership model[174]

Beyond these basics, several other key aspects should be considered for the business/partnership model, as detailed in the subsections below.

Governance: An agrivoltaic partnership will need to establish a clear governance structure for management and decision-making for the project. It is likely these governance structures would combine elements of both top-down and bottom-up governance approaches. Top-down elements such as an overarching decision-making body with representatives from across all stakeholder groups, including from traditionally marginalized groups, would be put in place to oversee operations and final decision-making. Bottom-up elements such as local farming cooperatives and other community member stakeholders would also have designated decision-making power at the local level to ensure community needs are incorporated across higher decision-making levels. For example, a committee with representatives from the mini-grid operator, local organizations, and other stakeholders could be formed. This committee would be responsible for making key operational decisions for the agrivoltaic project collaboration like roles and responsibilities, crop/livestock selection, planting/harvesting times, market decisions, use of revenue, PUE and other equipment, training needs and timing, standard operating procedures, tariffs, security, etc.

Community buy-in: As with mini-grid business models in general, to be sustainable and viable over the longer term, agrivoltaic solutions need to both demonstrate positive impact for the communities and secure community buy-in and the “social license to operate.” This means

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[174] Illustration by Andrew Bilich, NREL

being clear and transparent with potential opportunities and trade-offs during initial engagement and project development through project operation (see Section 4.11 Community Engagement below).

PUE: Section 4.6 PUE extensively details some of the important considerations for business models for agrivoltaic projects, including tariff structuring, selecting fit for context equipment, expanding PUE service beyond just the agrivoltaic site (e.g., through cooperatives or community service models), incentive-based financing for electricity consumption (see below), and parallel programming (see below). Upfront costs as well as ongoing costs for electricity and operations and maintenance will need to be balanced amongst the partners. There are several different models for this. Mini-grid developers could invest in PUE equipment directly and maintain ownership as part of research and development (generally supported by impact investors or philanthropic capital) charging only for the downstream electricity use (under standard tariffs or potentially specialized tariffs for agrivoltaics). Lease-to-own models could also be envisioned between the mini-grid operators and local cooperatives whereby local cooperatives utilize agrivoltaic proceeds to pay for the PUE assets over time.

Site access, security, and standard operating procedures: Mini-grid generation sites have both high-value equipment and many potential safety hazards and risks. Accordingly, any collaboration model with local partners will require development of specific standard operating procedures and close control of site access and security. For additional context on Haiti-specific site security considerations, see Section 5 Stakeholder Interviews below.

Training: It is likely that mini-grid developers will need to explore external partnerships to support initial training and capacity building. The ideal setup for this is a “train-the-trainers” type solution whereby mini-grid developer staff receive in-depth technical assistance from development partners, nongovernmental organizations, and other relevant groups on various facets of agrivoltaics, particularly on technical integration, agricultural production and harvesting, water management, site control, etc., that they can then utilize to manage, train, and support local partners. Both sides of this training will need to be deliberately paced and detailed to ensure sustainability of outcomes (see Section 4.10 Capacity Building below).

Parallel development projects: Mini-grid developers and their partners will need to proactively identify and align the agrivoltaic projects with other potential parallel programming in general development (e.g., community training programs/workforce development), energy access (e.g., PUE incentive programs, appliance financing), gender (e.g., workforce development, enterprise/entrepreneurial training), and especially food security and agricultural programming (e.g., value chains, agricultural extension training, specific crop development programs). For example, the agrivoltaic project could utilize some of its agricultural production to support local school or church lunch programs (both those run locally and those run through development partners and multi-laterals). This could not only help secure a stable off-taker for the agricultural production from the agrivoltaic site, but could also help expand the social impact and visibility of the agrivoltaic project and drive further community buy-in. This type of collaboration may also be able to secure additional results-based financing or other support from development partners for the agrivoltaic solution.

Data and metrics: To be successful, it will be important for agrivoltaic pilots to establish clear processes and capacity to collect and analyze data related to electricity consumption, agricultural productivity and yields, and value. Key potential metrics and data to track include:

- **Crop production**: Total area planted by crop; number of plants by crop variety; planting dates and length of growing seasons; crop yields per harvest (kg)[175]; plant height (cm); phenological stages (germination, vegetative growth, flowering, and fruiting); pest/disease pressure; water usage and water stress; market prices for crops (HTG per unit); and total revenue from crop sales (HTG).
    - It is important to note that the metrics for crop production reflect a broader learning-oriented approach to agrivoltaics, but simpler configurations may instead just track total crop yields (kg) and total revenue from crop sales (HTG).
- **Livestock production**: Total area of pasture; number of livestock; livestock production (kg or # of chicks per animal); water consumption; market prices for livestock products (HTG per unit); total revenue from livestock sales (HTG).
    - As with crop production, metrics could be simplified to just livestock production (total head/kg) and total revenue from sales (HTG).
- **Energy and mini-grids**: Electricity consumption from PUE over time (kWh); costs of operations, including electricity consumption (HTG); impact on mini-grid technical and financial performance (e.g., battery use vs. solar, staff time).

To help with data quality and entry, particularly for more research-oriented projects, it is recommended that agrivoltaic pilots establish clear protocols for agrivoltaic data. Reliably collecting and storing data for these key metrics will be one of the primary ways to track the success of mini-grid agrivoltaic installations in Haiti and demonstrate clear impact for both partners and the community. Digitally storing field data using laptops, tablets, and phones has become common practice to ensure data is archived and accessible when needed.[176] It will also be important for any pilot to adjust operations based on the observed data and ensure that there is a key feedback loop between indicators like production, revenue, water usage, prices, etc., to planting and other operational decisions for successive years for the agrivoltaic project.

4.10 Capacity Building

Early collaboration with local stakeholders, such as farmers, mini-grid developers, local cooperatives/associations, researchers, agencies, and/or other organizations, is important to understanding project-specific capacity-building and training needs. Stakeholder interviews highlighted the critical need to ensure that any capacity building is not done as a one-off, but rather over time through more side-by-side learning and support. Depending on the operational model and potential agreements, different training will be needed, but in general some key capacity-building needs include:

- **Electrical and site safety**: First and foremost, it is important that any person accessing a solar generation site have basic training on electrical safety and how to move and operate safely amidst potential generation site hazards. Training mini-grid developers on potential changes to solar infrastructure (e.g., alternative wire management) may also be necessary for ensuring the safety of on-site personnel and livestock.

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[175] For broader learning projects, crop data from the agrivoltaic site will need to be compared to a "control plot" (i.e., open-air agricultural production) nearby to understand the impact of the agrivoltaic microclimate on crop production.

[176] Data management applications (e.g., Google Suite, KoboToolbox, GIS Survey123, Absolute Forms, Dropbox/box, etc.) will be needed to accomplish this task, and it will be critical that whatever platform is utilized has offline capabilities given the often-unreliable access to internet and telecommunications in mini-grid communities.

- **Security and site access**: This will be different for different mini-grid operators, but there will be specific protocols, codes, keys, etc., for controlling access and security for the generation site that specific stakeholders will need training on.
- **Agrivoltaic production**: While many aspects are similar, agrivoltaics represents a new approach to agriculture from traditional farming, so mini-grid operators and their partners will need formal support and training to be able to effectively establish and operate the agrivoltaic solutions for their grids. Minor changes in production (e.g., changing the layout of the field) may be needed for the successful operation and management of mini-grid agrivoltaic systems. For farming, as agrivoltaics formalizes certain approaches for production, farmers will need additional training on use of new tools and approaches. In addition, agrivoltaic production creates a microclimate underneath the solar infrastructure that can alter agricultural variables (e.g., crop seasonality, water needs).
- **Planting/harvesting for agrivoltaics research**: For an agrivoltaic research pilot project, farmers/researchers will need to establish a control plot to be trained on planting and harvesting requirements necessary for valuable data collection. All farmers on-site should be trained on the same techniques and standards to ensure that all data has been collected using consistent methods.
- **Agricultural value streams and entrepreneurship**: Many farmers and cooperatives/associations are already involved at least informally with agricultural value streams, but additional training and capacity building for specific value streams and more formal entrepreneurship could help unlock additional opportunities and value for the agrivoltaic collaboration (e.g., turning groundnuts into mamba and selling that product directly). Many stakeholders will also benefit from sustained training on the financial and managerial aspects of agrivoltaics, particularly money management, digital solutions, marketing, etc.
- **Data management**: Agrivoltaics potentially has a wide variety of data needs, so training the mini-grid operator and its partners on how to set up and manage data flows for agrivoltaics is important. Training may be needed for specific data management applications and data-collection techniques to produce quality data sets. A key focus of data training should be on helping designated people and partners to understand the form entries and different measurements, focusing on very basic measurements (e.g., weight, height) that can then be used to do more complicated analysis on the back end.
- **Digital inclusion**: Alongside data management, agrivoltaic projects that integrate digital applications—for example, smart phone/tablet applications or dashboarding, both on-site through shared tablets as well as to individual devices, depending on ownership—for both general data management as well as decision-making (e.g., planting times), should ensure that effective capacity building with the digital platforms is provided in parallel.
- **Operation of PUE**: Depending on the PUE applications selected, it will be critical to provide direct hands-on training on how to utilize, clean, and maintain the different PUE equipment for people who may be responsible for operating the equipment.

As highlighted below, enabling training opportunities across all these areas offers a significant entry point for advancing gender equality. It is also important to recognize that training needs, timing, and approach may be different for men and women due to their roles in everyday life, so it is important to ensure that training methods are tailored, appropriate, and supportive across genders.

It is likely that developers will want to hire a specific person to oversee and manage the agrivoltaic work and collaboration with other groups. It will also be important in Haiti to make sure that training and operational materials are developed in Haitian Creole, including pictographic instructions, where possible. It is also important to consider a “train-the-trainers” approach to help build capacity for the mini-grid developers to support local partners with an eye toward the need for long-term sustained engagement to build holistic and long-lasting learning.

4.11 Community Engagement

Lessons learned from previous agrivoltaic project efforts[177] and stakeholder interviews in Haiti demonstrate the significant role of community engagement in ensuring development outcomes that are socially acceptable, technically sound, and economically viable. Effective community engagement is grounded in principles of justice, equity, diversity, and inclusion. For agrivoltaics, this entails collaboration with varied stakeholders—farmers, landowners, community members, local organizations, local and national government, decision makers, developers, development partners—across all project phases, from siting to design, as well as maintenance and succession planning.

Proactive community engagement should be aimed at building trust and overcoming uncertainty with business models. Agrivoltaic project success requires balancing diverse priorities and needs, which underscores the importance of intentional engagement, particularly with agricultural actors. Absent this critical input, mini-grid developers may remain constrained in their ability to develop business models that feature equitable payment structures, ownership agreements, and maintenance protocol; proper community engagement is key to enabling viable outcomes for all.

Different elements of community engagement are highlighted throughout the other sections (particularly working alongside local cooperatives), and specific strategies will depend on who is being engaged and the project context itself; however, general community engagement-planning considerations for agrivoltaic projects include: (1) participatory planning; (2) impact assessment; (3) clear roles, responsibilities, and agreements; and (4) information sharing and communication (Figure 14).

Figure 14. Overview of key community engagement planning considerations[178]

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[177] Macknick, Jordan, et al. 2022. *The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study*. https://www.nrel.gov/docs/fy22osti/83566.pdf.

[178] Illustration by Thomas Hickey, NREL

Participatory planning is a process that emphasizes diverse stakeholder representation at all stages of a project cycle. Participatory planning for agrivoltaics balances technical solar knowledge of mini-grid developers with cultural knowledge of local stakeholders, particularly smallholder farmers and agricultural cooperatives, to co-develop equitable project outcomes and build trust. Research concerned with the role of stakeholder engagement in agrivoltaic development highlights the importance of early collaboration with farmers to inform proper solar design that supports operational needs[179] as well as broader consultation that addresses localized project preferences and concerns.[180] A key element of this is consistent, transparent, and accessible stakeholder meetings that:

- Start at project origination and recur regularly throughout the project cycle, according to an established timeline.
- Are scheduled at times and in places that are accessible to all stakeholders. For example, it is important to understand gender dynamics and social responsibilities that may limit certain groups from being able to participate at certain times.
- Provide accessible materials and information; for the rural Haiti context, this will necessarily include pictographic materials and materials in Haitian Creole.
- Set general expectations around participation and establish protocols for decision-making.
- Solicit input on various project elements, including but not limited to siting preferences, system design (particularly ensuring that agrivoltaic systems support existing agricultural practices and meet requirements for energy production), archetypes and crop/livestock selection, PUE, business model, governance, and community benefits (e.g., job creation, alignment with other programs, revenue sharing).
- Identify project priorities across groups and develop a strategy to meet multiple needs at once.

Impact assessment identifies and manages project-related impacts (both positive and negative) across social, economic, and environmental dimensions. Impact assessment for agrivoltaics involves evaluating: (1) geospatial factors, such as effects on ecosystems or culturally sensitive areas; (2) stakeholder perspectives on anticipated project impacts; and (3) broader system considerations, particularly potential impacts on land availability, local food systems, and social groups. It is likely that these impact assessments can be integrated into broader mini-grid assessment processes.

Clear roles, responsibilities, and agreements are critical to the long-term operation of an agrivoltaic project. Community engagement should inform the appropriate business models, ownership and personnel considerations, standard operating procedures (including for site access and security), and long-term management plans. For agrivoltaics in Haiti, this could include an emphasis on local workforce development with clear roles across project components, including cultivation, post-harvest processing, and distribution. Gender dynamics should be proactively considered, with special attention afforded to opportunity creation for women (see Section 4.12 Gender below). Just and transparent agreements regarding financial aspects of the project are also critical. Improving mini-grid operator capacity to manage

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[179] Pascaris, Alexis, Chelsea Schelly, and Joshua Pearce. 2020. "A First Investigation of Agriculture Sector Perspectives on the Opportunities and Barriers for Agrivoltaics." *Agronomy* 10. https://www.mdpi.com/2073-4395/10/12/1885.

[180] Pascaris, Alexis, Chelsea Schelly, Mark Rouleau, and Joshua Pearce. 2022. *Do agrivoltaics improve public support for solar? A survey on perceptions, preferences, and priorities*. https://doi.org/10.1007/s44173-022-00007-x.

agrivoltaic projects and prioritizing agricultural expert representation in project development can ensure business models and agreements are viable and sustainable long-term.

Information sharing and communication across project stakeholders is the foundation of a sustainable project. For Haiti, it is important that communication materials and conversations are in Haitian Creole and that pictographic examples are used where applicable. Relative lower literacy rates suggest that tactile learning and communication will be most effective for community engagement and project operation. As agrivoltaic projects emerge in Haiti, ensuring robust communication channels between all actors involved is particularly important for strengthening the research feedback loop—early lessons learned can improve future agrivoltaic developments if information and best management practices are shared.

4.12 Gender

Women in Haiti are considered the backbone of the Haitian economy, particularly in the informal labor market where they are key players in the supply chain in areas such as agricultural processing, and marketing of agricultural goods.[181] However, Haiti is a patriarchal society with gender norms that limit women's roles in the formal economy. In fact, Haiti ranks 163rd in the world for gender equality (measured across health, empowerment, and employment/labor dimensions through the United Nations Development Program Gender Inequality Index).[182] While legal frameworks have created provisions to enact policies aimed at promoting gender equality, these are largely absent in practice.[183,184]

As a result, cultural beliefs and norms determine women's roles in society, their access to resources, and their decision-making power. Haitian women can be seen taking larger or sole roles in caregiving and thus may lack the time to engage in paid work outside the home. This status also leaves them more vulnerable in times of crisis, as Haitian women have been noted to be disproportionately impacted by rising poverty.[185] However, women are noted to have greater decision-making capabilities within the household, especially in decisions regarding household expenses[186,187]

Mainstreaming gender in agrivoltaic projects can help women in two main ways. First, it can help reduce physical labor and hours spent in their existing roles by providing access to processing equipment and water pumping. Second, it can help expand income-generating opportunities, particularly in agriculture and agri-business. Agrivoltaics can also integrate into other broader frameworks for gender mainstreaming and energy access; for example, EarthSpark's Feminist Electrification methodology,[188] which identifies five key pillars to support gender mainstreaming in mini-grid and energy access projects, namely, infrastructure planning,

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[181] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[182] UNDP. 2022. "Gender Inequality Index." https://hdr.undp.org/data-center/thematic-composite-indices/gender-inequality-index#/indicies/GII.

[183] Kellum, Jane, Sue Telingator, Kenise Phanord, and Alexandre Medginah Lynn. 2020. *USAID/Haiti Strategic Framework Gender Analysis Report.* https://banyanglobal.com/wp-content/uploads/2021/01/USAID-Haiti-Strategic-Framework-Gender-Analysis.pdf.

[184] Conversations with gender advisor for USAID-Haiti mission as part of stakeholder engagement.

[185] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[186] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[187] Conversations with gender advisor for USAID-Haiti mission as part of stakeholder engagement.

[188] EarthSpark International. "Feminist Electrification." https://www.earthsparkinternational.org/feminist-electrification.html.

employment and training, support for local business, domestic energy use, and community resource availability.

Mainstreaming gender is not only beneficial but also essential to ensuring that existing gender inequalities are not worsened. Designing a "gender-blind" agrivoltaic project that does not deliberately integrate gender carries a significant risk of reinforcing the power dynamics between men and women should the economic potential be accessible only to men. This would further exacerbate gender inequalities and the structures that enable them.

Based on stakeholder interviews, existing gender frameworks, and ongoing agrivoltaic/agricultural research, several key entry points for gender mainstreaming in potential agrivoltaic pilot projects were identified for mini-grid developers and program managers (Table 10).

Table 10. Entry Points for Gender mainstreaming for Agrivoltaic Projects

Entry Point	Description
Project Design	**Baseline:** In Haiti, there are barriers to women being included in the project design stage. With gender norms, women tend to be excluded from social decision-making and governance, particularly for land-use. Further, as a result of domestic tasks and unpaid labor for childcare, cooking, fuel/water collection, etc., women also have limited time and windows of time in which they can engage in meetings and conversations about potential project opportunities.[189,190,191] **Opportunity for agrivoltaics:** Agrivoltaic projects should prioritize women's input during the design stage to ensure that the projects are effectively identifying, understanding, and incorporating the key opportunities and differentiated needs for women in project scoping and activities. To do this, it is critical to have in-person meetings that specifically engage women, including by making sure they are at times and in places that are accessible for women and that other support like childcare is provided as appropriate.
Partnerships	**Baseline:** Women's cooperatives and associations are prevalent throughout Haiti, particularly for farming and agricultural activities. They range in formality and size, but generally are active across a variety of value chains in Haiti. As such, they are strong organizing forces for formal and informal agriculture. Despite this, they tend to have fewer available resources than other organizations. **Opportunity for agrivoltaics:** Women's groups, particularly farming cooperatives and associations, are key potential partners that mini-grid developers should engage in the development of agrivoltaic projects. In many ways, partnerships directly with women's groups can help identify, streamline, and enhance opportunities for gender mainstreaming in other entry points (e.g., partnering on agricultural activities, expanding market access, training, etc.). Stakeholders echoed this as an important pathway for the success of past agricultural/PUE projects.[192]

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[189] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[190] Kellum, Jane, Sue Telingator, Kenise Phanord, and Alexandre Medginah Lynn. 2020. *USAID/Haiti Strategic Framework Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2021/01/USAID-Haiti-Strategic-Framework-Gender-Analysis.pdf.

[191] Conversations with gender advisor for USAID-Haiti mission as part of stakeholder engagement.

[192] EarthSpark International. "Powering Livelihoods and Community Services Through Productive Uses of Energy." https://www.earthsparkinternational.org/powering-livlihoods.html.

Entry Point	Description
Agricultural Activities	**Baseline:** At least 38% of Haitians working in the formal agriculture sector are women.[193] In agricultural enterprises, men typically are responsible for planting and weeding, while women take up roles in the rest of the agriculture value chain such as harvesting, processing, marketing, and selling. Women also can face challenges for land tenure and ownership, access to agricultural inputs (e.g., tools, seeds, etc.), and access to equipment (e.g., processing—see below).[194] **Opportunity for agrivoltaics:** Agrivoltaic projects can identify the key roles that women have in regional agriculture and inform outcomes that help reduce their physical and time burden and enhance their income opportunities. For example, if agrivoltaic project developers partner with women farmers or farming groups, they can provide access to good quality farmland as well as key inputs like tools and seeds, thereby increasing productivity potential and enhancing income opportunities from crop sales. Agrivoltaic projects can also empower women in decision-making on land use (e.g., on crop planting). Further, agrivoltaic projects that incorporate irrigation or water pumping can help with efficient water management, leading to improved crop yields and an increase in income. Irrigation capabilities in agrivoltaic projects can help reduce the time burden on women and children collecting water.[195] Where women raise livestock such as chickens and sheep, agrivoltaics can also allow for livestock grazing.[196]
Agricultural Processing	**Baseline:** Agricultural post-harvest processing activities include crop drying, threshing, milling, storing, and packaging and slaughtering (in the case of animal husbandry). Haitian women typically dominate this sector and are key contributors to the revenue generated from these activities. However, they tend to lack access to tools, equipment, and financial support, and end up doing most of this processing work by hand, creating significant time and physical burden and limiting income-generation potential.[197] **Opportunity for agrivoltaics:** Agrivoltaic projects can integrate PUE appliances to not only reduce the physical/time burden of manual processing but also enhance the value potential of the crops and improve the ability to store and transport products. For example, as explored in Section 4.6 PUE above, de-shelling machines and grinders can be deployed to reduce the physical and time burden of manually processing groundnuts and enhance their potential value in the market. Cold storage can also reduce post-harvest losses and improve revenue. Stakeholders also highlighted key opportunities to integrate solar dryers or dehydrators to help support fruit production, particularly in the breadfruit value chain.
Markets and Distribution	**Baseline:** Haitian women play a leading role in linking rural producers and urban consumers, commonly referred to as *Madan Sara (women traders).*[198] Their role is highly valued in the country, as they ensure that goods are properly distributed and reach remote consumers.[199] Their participation in market activities also gives them bargaining power in the household in how the

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[193] Research Technical Assistance Center. 2021. *Haiti Market Analysis: Sud and Grand'Anse Departments*. https://pdf.usaid.gov/pdf_docs/PA00X97B.pdf.

[194] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[195] FAO. 2023. "One Drop at a Time." https://www.fao.org/science-technology-and-innovation/resources/stories/one-drop-at-a-time-silotte-mervil-an-innovative-haitian-farmer/en.

[196] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[197] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[198] Kellum, Jane, Sue Telingator, Kenise Phanord, and Alexandre Medginah Lynn. 2020. *USAID/Haiti Strategic Framework Gender Analysis Report.* https://banyanglobal.com/wp-content/uploads/2021/01/USAID-Haiti-Strategic-Framework-Gender-Analysis.pdf.

[199] Shenaz Hossein, Caroline. 2015. "Black women in the marketplace: everyday gender-based risks against Haiti's madan saras (women traders)." *Work Organisation, Labour & Globalisation.* https://www.jstor.org/stable/10.13169/workorgalaboglob.9.2.0036.

Entry Point	Description
	income from agricultural production is being used.[200] Their role is also highly risky, and these women are increasingly vulnerable to crimes such as kidnapping, robbery, assault, and rape. **Opportunity for agrivoltaics:** Agrivoltaic projects can help provide alternative income streams, formalize some of the trading, and provide clearer off-takers (e.g., through partnerships with school lunch programs) particularly through collaboration with associations and cooperatives. Further, agrivoltaic projects need to be systematic in evaluating risk factors involved with marketing and distribution of products from the site to ensure that the project does not heighten baseline vulnerabilities.
Training	**Baseline:** Due to the barriers outlined above, current data shows that compared to men, Haitian women have less technical knowledge and underdeveloped managerial skills and capacity.[201] This is especially true for the agricultural sector, where women tend to have more informal roles and less formalized training. **Opportunity for agrivoltaics:** Agrivoltaic projects can provide specific upfront technical training (as well as refresher trainings at a regular cadence) for women to help develop new skills and strengthen existing skills. These trainings should not only cater to the technical aspects of agricultural activities (e.g., planting/harvesting timing, water use), agricultural processing (e.g., operations and maintenance of PUE appliances), and site safety (e.g., electrical safety), but should also include information on financial aspects, managerial skills, and agricultural value chains. Trainings that include both men and women have seen greater success, as men have been noted to accept the change in women's roles when they equally participate in the training sessions.
Workforce Development	**Baseline:** Haitian women often have much lower participation in the formal labor economy and also have lower wages compared to men.[202] Due to structural barriers outlined above women also bear a disproportionate burden of unpaid labor such as caretaking in the household, cooking, and fuel/water collection that does not allow them to explore paid opportunities outside the home.[203] However, Haitian men have been shown to help with childcare when their wives increased their economic activities.[204] **Opportunity for agrivoltaics:** Agrivoltaic projects can not only create direct employment/income opportunities for women both in expansion of agricultural activities and downstream sales and marketing, but also on the mini-grid operator side in roles like research or site manager for the agrivoltaic project. Given the nature of the work, in creating or supporting these new roles, agrivoltaic projects can look to build in flexibility for timing to help alleviate the strain of balancing other responsibilities, particularly management of household activities.

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[200] Springer, Joanna, et al. 2022. "Exploring women's bargaining power in Haitian agricultural households." *Journal of International Development*. https://onlinelibrary.wiley.com/doi/full/10.1002/jid.3641.

[201] Kellum, Jane, Sue Telingator, Kenise Phanord, and Alexandre Medginah Lynn. 2020. *USAID/Haiti Strategic Framework Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2021/01/USAID-Haiti-Strategic-Framework-Gender-Analysis.pdf.

[202] Kellum, Jane, Sue Telingator, Kenise Phanord, and Alexandre Medginah Lynn. 2020. *USAID/Haiti Strategic Framework Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2021/01/USAID-Haiti-Strategic-Framework-Gender-Analysis.pdf.

[203] Kellum, Jane, Ulrick Jean Claude, and Stephen Louis. 2022. *USAID/Haiti Economic Growth and Agricultural Development: Gender Analysis Report*. https://banyanglobal.com/wp-content/uploads/2022/05/USAID-Haiti-EGAD-GA-Final-508.pdf.

[204] USAID/Haiti DO2 PAD Gender Inputs. 2018.

Entry Point	Description
Financial and Digital Inclusion	**Baseline:** Women tend to have lower financial and digital literacy in Haiti, and face significant challenges for access to finance, particularly for loans as well as access to technology and digital solutions (e.g., smartphones, computers, internet access, etc.).[205] **Opportunity for agrivoltaics:** As highlighted above, agrivoltaic projects can help provide training on financial aspects of agricultural activities. Further, there is opportunity for agrivoltaic efforts to integrate smartphone applications or dashboarding (both on-site through shared tablets as well as to individual devices, depending on ownership) for agricultural variables or production (e.g., temperature, harvest/planting timelines, water pumping, crop prices, etc.). This has been done successfully in smallholder farmer projects across Africa and has been shown to help advance opportunity for women. This could also be coupled with other digital literacy efforts from the mini-grid developers (e.g., kiosks for electricity consumption, SMS outreach, etc.). Finally, where possible, mobile money (and related training) can be incorporated for at least paying for PUE electricity from the mini-grid developer (if the developer has mobile money set up) and/or payment for crop production.
Community Engagement	**Baseline:** Women have differentiated needs and opportunities, particularly when it comes to agriculture and potential agrivoltaic projects, so it is critical to ensure that these perspectives are proactively identified and integrated into project design. Community engagement is core to this process, but women can be overlooked if not engaged intentionally (see Section 4.11 Community Engagement above). **Opportunity for agrivoltaics:** Including women in focus groups as well as in interviews in every stage of the project design and implementation will help bring women into the spotlight, highlighting their needs, challenges, and the unique barriers they face. As technological interventions do not always meet women's needs, it is essential to have direct meetings and conversations with the women's groups. For example, women might not always have access to mobile phones and/or the time to talk to project managers during normal operating hours.

Outside of these specific entry points, there are two overarching principles for gender mainstreaming in agrivoltaic projects:

1. **Adhering to the no-harm principle**: Projects should ensure that any intervention (such as a new employment opportunity or having women in control) will not worsen women's status quo. This means that projects should evaluate potential risks and outcomes before implementation, particularly through stakeholder engagement processes and social impact assessments within the region and community where it is planned.
2. **Holistic consideration of gender entry points**: Projects should integrate these considerations holistically rather than in isolation. For example, equipping women's groups or farmers with PUE equipment for de-shelling or grinding agricultural produce but not having any training on how to operate and maintain the appliance will make them dependent on external members who may or may not be willing and/or have the resources to help. **Nevertheless, having gender as a focal point in any area is better than none.**

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[205] Springer, Joanna, et al. 2022. "Exploring women's bargaining power in Haitian agricultural households." *Journal of International Development.* https://onlinelibrary.wiley.com/doi/full/10.1002/jid.3641.

5 Stakeholder Interviews

Introduction
Background
Methodology
Results and Key Considerations
Stakeholder Interviews
Limitations and Next Steps
Discussion and Recommendations

The stakeholder interviews effort was designed to identify challenges and opportunities for agrivoltaic implementation in Haiti. A total of 8 interviews with 15 individuals across 9 organizations were conducted by the research team, including USAID, the Inter-American Development Bank, the Global Energy Alliance for People and Planet, Fonkoze, the Ministère des Travaux Publics, Transports et Communications, EarthSpark International, DigitalKap, Fondation Bonne Recolte, and Harvest Craft. Insights from these interviews informed the previous sections but are also discussed in detail in the following subsections.

5.1 Agriculture and Energy: Interconnections in the Haitian Context

The challenge of energy access in Haiti cannot be decoupled from the challenge of food security. Stakeholders discussed the interconnection between these sectoral challenges and the necessity to view sustainable development in Haiti more holistically—from an agriculture-energy nexus perspective. Stakeholders noted that past siloed approaches have led to project implementation without long-term success, which underscores the importance of cross-sectoral collaboration (Figure 15).

Food security in Haiti was stressed as a more acute problem compared to energy access. Issues around land and water access, diminished quality of farmland, lack of market linkages, and commerce restrictions were raised by study participants as central challenges for the agricultural sector in Haiti. Participants highlighted that the most distinct barrier to improved food security is related to post-harvest loss as a result of limited availability of agricultural PUE (e.g., cold storage, small-processing machinery). Stakeholders identified that financing options for PUE remain limited in Haiti, highlighting the need to focus and invest in technological solutions that can provide benefits across sectors (e.g., agrivoltaics), accounting for the dynamic relationship between electrification and food security.

Haiti's energy sector has its own set of challenges that intersect with the agricultural sector. Foremost for stakeholders was a lack of access to private finance, uncertain regulatory environments, and barriers to accessing supporting factors like grid insurance that are currently slowing solar mini-grid development in Haiti. Lack of access to finance compounds with challenges around land access, particularly in areas where land is allocated for agricultural purposes. Stakeholders elaborated on how land suitable for solar is hard to identify and secure, and that the Haitian land tenure system presents complexities when thinking about managing land for dual purposes (solar and food production). The environmental and social impact assessment processes associated with land acquisition and conversion for energy use were raised as a critical consideration for cross-sectoral project success. The existing bureaucratic process complexity for mini-grid development in Haiti was raised by all stakeholders, emphasizing that political feasibility is a key consideration for future projects.

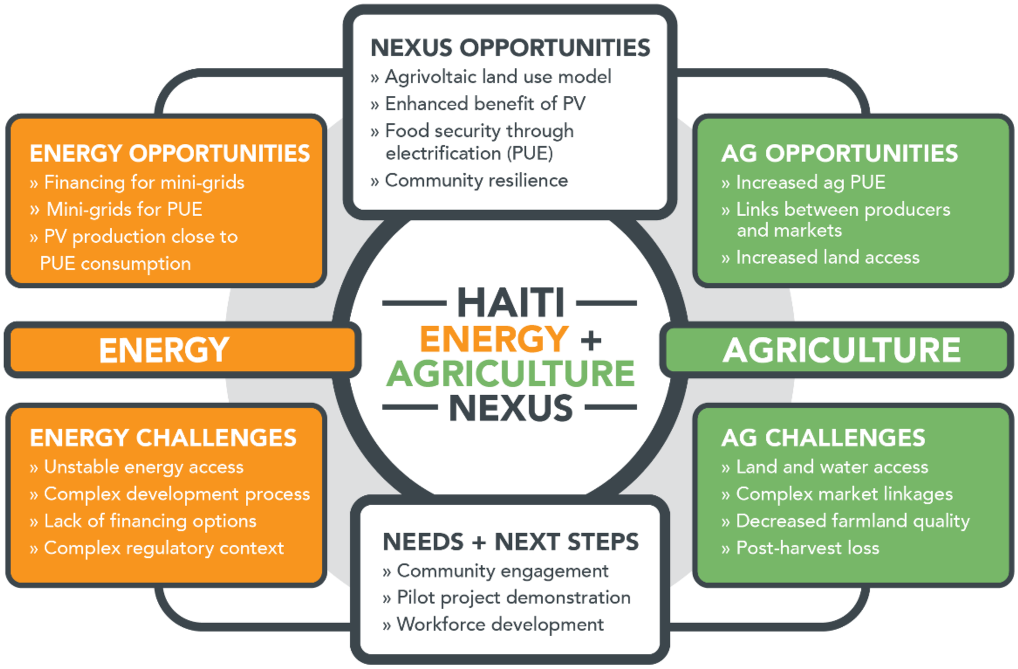

Figure 15. Stakeholder highlights for key challenges and opportunities for agrivoltaics and the energy-agriculture nexus[206]

5.2 Opportunities at the Agriculture-Energy Nexus in Haiti

A core focus of the stakeholder interviews was to identify opportunities at the agriculture-energy nexus in Haiti. Discussions centered on the potential benefits of aligning sectoral goals more broadly and considered the specific role of agrivoltaics in enabling these benefits. Three key opportunities emerged: enhanced impact of solar; improved food security; and strengthened community resilience.

Enhancing the impact of solar on the agriculture sector is a critical interest. Stakeholders acknowledged a need for mini-grid operations to intentionally intersect with agriculture, seeing the benefit to farmers and broader solar development from incorporating agricultural considerations into solar projects. Agrivoltaics was considered a potentially powerful lever for facilitating socio-economic development in Haiti, including local community benefits such as increased added value of land, new employment opportunities, and improved agricultural resilience. Across all stakeholder groups engaged, agrivoltaics was regarded as a meaningful strategy to address food and energy challenges and create mutually beneficial impacts on both sectors. Further, agrivoltaics was seen as a way to enhance the positive impacts and lessen potential negative environmental and social impacts of developing solar (e.g., conversion of farmland), particularly within environmental and social impact assessment frameworks.

Improving food security through agricultural electrification is a vital priority. Participants elaborated on how integrating more robust agricultural PUE into solar mini-grids, specifically cold storage, post-harvest processing machinery, and irrigation, would mitigate food waste, create value-added products, and improve mini-grid and agricultural productivity. The

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[206] Illustration by Thomas Hickey, NREL

opportunity to leverage PUE (water pumping and irrigation) to alleviate water scarcity challenges for farmers was further discussed as critical, specifically for northeastern communities that struggle with drought. Electrification opportunities were stressed as the most pressing need at the agriculture-energy nexus, suggesting that solar mini-grid development could be more strategically leveraged to improve food security.

Strengthening community resilience through agrivoltaics is a promising strategy. Study participants discussed the potential technical, economic, and social benefits that agrivoltaics could provide agricultural communities in Haiti and viewed agrivoltaics as a unique innovation well suited to improve local resilience. Of specific interest was the opportunity to enable farmer access to land that is secure. Agrivoltaics allows for farms to operate within an enclosed solar array, which stakeholders considered a unique means to minimize risk of theft for farmers. Participants also discussed how the small-to-medium-scale nature of farming in Haiti would lend well to integration within a solar array, particularly noting hand-harvested specialty crop production as a relevant opportunity. Further, the potential to improve livelihoods and yields was raised. Stakeholders noted that though livestock-based agrivoltaic systems are less management-intensive, crops hold greater potential to create positive impact on livelihoods and revenue diversification, especially in instances where shade from solar panels could reduce water demand in drought areas. Beyond these benefits, participants perceived agrivoltaics as a prime opportunity for community engagement, capacity building, and gender mainstreaming.

5.3 Challenges for Agrivoltaics in Haiti

Discussions on the agriculture-energy nexus in Haiti revealed several potential challenges for agrivoltaics, although stakeholders were still largely supportive of the agrivoltaic concept. In particular, stakeholders highlighted uncertainty with business models, issues with political feasibility, and implementation risk as key challenges for implementation of agrivoltaics.

Socio-political and economic uncertainties may complicate agrivoltaic development. Most stakeholders were new to the concept of agrivoltaics, noting that there currently is no existing blueprint for the execution of such projects in Haiti. This lack of experience may add a dimension of uncertainty to implementation and a need to apply an iterative and flexible approach—continuously adjusting project plans to ensure alignment with contextual factors such as security issues and changing politics. Some stakeholders noted low internal capacity to pursue agrivoltaic development and concerns around potential increased costs. They also expressed concern about an absence of technical skills to manage agrivoltaics within the local communities. This "liability of newness" and cost-benefit uncertainty[207] is a common phenomenon among practitioners considering pathways to deliver agrivoltaic solutions, however this also presents an opportunity for increased community engagement and trainings to increase workforce capacity to care for agrivoltaic installations at the local level.

Establishment of business models for agrivoltaics is still in its nascent stage in Haiti. Participants regarded the business model as potentially the most complex yet most important aspect of agrivoltaic development. Unknowns around proper agreements, beneficiaries, legal considerations, and liability present hurdles to participants considering how to define a cost-effective and equitable business model for agrivoltaics. Study participants also noted a need to consider best practice approaches for stakeholder management, specifically cross-sectoral and interinstitutional relationship development. The need for effective collaboration strategies

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[207] Pascaris, A. S., A.K. Gerlak, and G.A. Barron-Gafford. 2023. "From niche-innovation to mainstream markets: Drivers and challenges of industry adoption of agrivoltaics in the US." *Energy Policy.* https://www.sciencedirect.com/science/article/pii/S0301421523002793.

extends to regulators and financiers as well. Stakeholders explained how navigating organizational siloes in Haiti can be a challenge, especially in the context of agrivoltaics, as a clear regulatory pathway has yet to be established. However, stakeholders did not highlight any definitive regulatory hurdles within the PHARES program for agrivoltaics, but rather encouraged mini-grid developers to pursue agrivoltaic implementation permissions separate from PHARES to create process simplicity. Finally, stakeholders noted the importance for agrivoltaic developers to be clear and transparent about potential increased complexities and costs associated with agrivoltaics to ensure transparency with local communities.

Lack of knowledge around agrivoltaic implementation risks may prevent adoption. Key risk considerations highlighted by stakeholders were technical complexities with deployment feasibility and agrivoltaic site management and security. How to protect both humans and the operational equipment at agrivoltaic sites was frequently raised as a key risk to address in the development process. Similarly, stakeholders stated that operations and maintenance technical needs may be difficult to manage for agrivoltaics but are key to ensuring project sustainability. Properly integrating site personnel access, agricultural needs such as irrigation, and operations and maintenance activity in a safe and coherent manner was discussed as complicated, but essential, especially given the small footprint of current mini-grids in Haiti. At present, stakeholders highlighted the need for support on how to properly design and manage cost-effective agrivoltaic projects that balance the various priorities, considerations, and actors.

5.4 Needs and Next Steps for Agrivoltaics in Haiti

The central objective of the stakeholder interviews was to identify key needs relevant to promoting agrivoltaic solutions in Haiti. Stakeholders highlighted a need to focus on deep community engagement, workforce development, and implementation of a pilot project to maximize the potential benefits of agrivoltaics and reduce development complexities and risk.

Deep community engagement is needed to inform locally relevant, economically viable, and technically sound projects. Stakeholders consistently highlighted the need for intentional community engagement and partnerships with local cooperatives as paramount for ensuring the agrivoltaics projects were tailored and delivering benefits for local communities. Stakeholders also highlighted that identifying a “project champion” early on was important to help emphasize and facilitate strong relationships among diverse stakeholders across all phases of project development to drive outcomes that are socially, economically, and technically viable.

Managerial capacity building and workforce development can overcome short-term uncertainties and improve long-term project sustainability. Stakeholders highlighted a need to develop close hand-in-hand training and collaboration between all parties so that the agrivoltaics projects can develop the requisite human capital for long-term sustainability. Further, stakeholders consistently noted that workforce development should emphasize tactile learning and creation of gender entry points, as well as specific training for managerial aspects of agrivoltaic projects.

Technical and economic proof of concept through pilot project demonstration is a fundamental next step for agrivoltaics in Haiti. Proper business models, workforce development, and cost-benefit analysis is dependent on Haiti-specific research that demonstrates the technical, economic, and social viability of combining agriculture and mini-grids. Stakeholders highlighted that field testing is needed to validate assumptions around agricultural compatibility and financial viability, understand potential impacts on soil and water quality, and inform site construction protocols that reflect the realities of environmental conditions in Haiti, especially the need for hurricane-resilient infrastructure.

Patient and flexible support to respond to the dynamic challenges in Haiti is essential to catalyze pilot project success. Due to the novelty of agrivoltaics in Haiti, pilot projects should be simple and justified, with clear criteria for site and crop selection. Implementers should be willing to accept and learn from various implementation approaches, even those that are not traditionally “successful.” A phased approach to testing and validation was suggested by stakeholders promoting a pilot project, which would begin with a crop feasibility assessment and intentional community engagement and partnership building, followed by the addition of PUE. Stakeholders emphasized that key impact metrics should be defined and collected, including impact on downstream energy production/consumption and economic impacts. Additionally, a cross-comparative analysis of impacts, costs, and benefits between standard mini-grid development and agrivoltaics was raised as a particularly interesting approach to inform decision-making. All stakeholders expressed interest in collaboration on pilots, pending availability of funding. Coordination with existing projects, as well as consideration for gender equity and social inclusion, were stressed as key enablers to pilot study success.

6 Limitations and Next Steps

This research had several limitations that should be considered and addressed by future research and pilot projects.

First, given the project timelines and security situation in Haiti, this effort was conducted via a rapid desk assessment—meaning that no specific evaluations were able to be conducted in-country on an actual mini-grid site. While the research team worked with stakeholders and available data/research to understand the potential context for the agrivoltaics and model representative systems, there are likely other nuances, considerations, and in-country practicalities that would need to be accounted for in tailoring and developing an agrivoltaic solution for mini-grids in Haiti. These would need to be surfaced and identified through a pilot project application for an actual mini-grid site in Haiti. Further, this report focused on identifying the top-level considerations, opportunities, and challenges for an agrivoltaic project for mini-grids in Haiti. More granular detail for pilots would need to be assessed to fully inform agrivoltaic development.

As highlighted throughout, this analysis looked at costs and benefits at a project level, but one of the most important next steps for future pilot projects is to work deliberately with potential stakeholders to develop equitable agreements for balancing potential revenue, responsibilities, and costs.

Further, Haiti in general has challenges with data availability, data quality, and data recency. Data availability gaps included market prices for certain crops and products (e.g., goat meat prices were used to estimate sheep meat prices), food chain losses for animal products, irrigation needs, energy requirements for irrigation, and costs for certain equipment. Data quality issues included yield/production estimates that did not reflect impacts from microclimates created by the panels (e.g., shading or temperature changes), or improved agrivoltaic production. Several “older” data sources were also used for elements like irrigation needs, agriculture/energy sector context, and crop yields. It will be important to deliberately refine and field validate these data during pilot development and implementation.

Arguably the most pressing limitation of this study is the limited availability of Haiti-specific cost estimates for agrivoltaic integration (e.g. capital expenditure for equipment, labor, PUE, etc.). The study included representative assumptions wherever possible, but for certain elements like the overall cost of agrivoltaic setup and integration it was not possible to estimate with any degree of confidence at this juncture. Costs will be one of the primary considerations for potential pilot projects, thus it will be important to work directly with suppliers and mini-grid developers to refine potential cost adders and estimates for specific locations.

To focus on the specific agrivoltaics considerations, the analysis also simplified the mini-grid and agrivoltaics model to just focus on the agrivoltaics electricity consumption, assuming that downstream electricity consumption for other households and businesses would not be impacted by the relatively small electricity consumption from the PUE models. While reasonable given the size of the PUE applications considered, there may be additional downstream impacts to consider. Similarly, the analysis assumed that the PUE from agrivoltaics could be covered by the solar + storage, however for some of the 24-hour PUE applications like cold storage and egg incubation, agrivoltaics may increase diesel fuel usage for depending on the specific system sizing/components of the mini-grid and the other loads on the system. Further, this analysis adopted a limited frame for evaluating PUE, and did not closely model the impact of adding PUE on mini-grid tariffs, service reliability, load curves, and technical/operational efficiencies.

The focus of this report was to provide a holistic view of potential agrivoltaics models, but simplified versions that solely focus on core agricultural production rather than the extended agricultural research space could be envisioned and explored by future efforts.

Finally, there are shortcomings for the qualitative interview approach, particularly a smaller and non-statistically representative sample. The research team worked to connect with a variety of key stakeholders working in Haiti, including development partners, government agencies, engineering, procurement, and construction firms, mini-grid developers, and agricultural nongovernmental organizations. However, the team was unable to connect directly with local communities and farming cooperatives/associations due to limited communication channels and access to key informants. This limited the project's ability to fully validate key parameters like crop selection, PUE, capacity-building needs, and business/collaboration models. Despite lacking input from local community stakeholders, the insights derived through engagement of other key organizations provide an indicative representation of perspectives on agrivoltaics in Haiti. As highlighted in Section 5 Stakeholder Interviews, co-developing the solutions with local farmers and communities will be imperative to the development and long-term viability of any agrivoltaic project. Therefore, future efforts should work to connect directly with local farmers through local cooperatives or other means.

7 Discussion and Recommendations

Introduction
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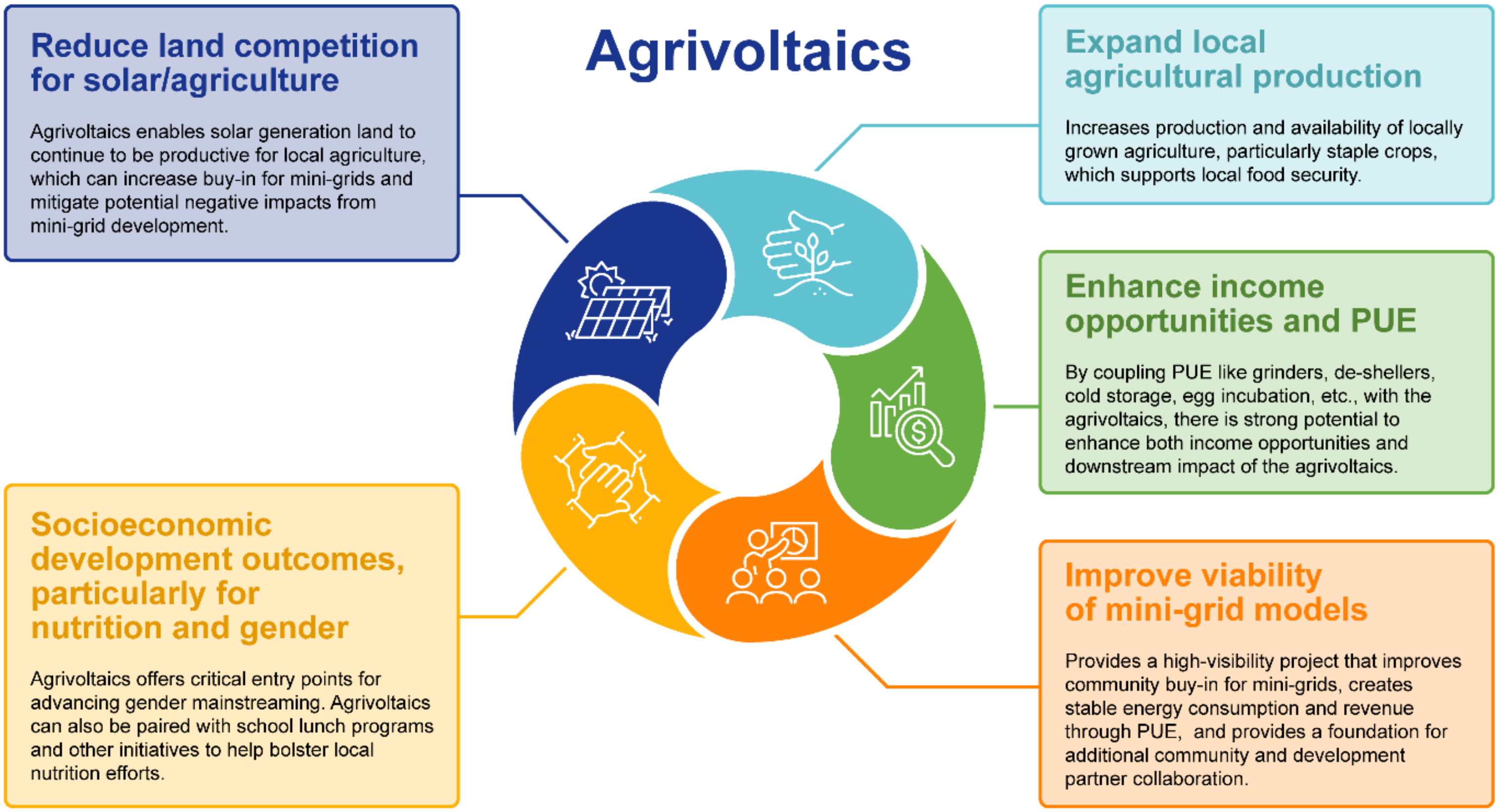
Stakeholder Interviews
Limitations and Next Steps
Discussion and Recommendations

7.1 Benefits of Agrivoltaics for Mini-Grids

Overall, the research highlighted that agrivoltaics can potentially have significant cross-cutting benefits for mini-grid models and their stakeholders in Haiti (Figure 16).



Reduce land competition for solar/agriculture

Agrivoltaics enables solar generation land to continue to be productive for local agriculture, which can increase buy-in for mini-grids and mitigate potential negative impacts from mini-grid development.

Expand local agricultural production

Increases production and availability of locally grown agriculture, particularly staple crops, which supports local food security.

Enhance income opportunities and PUE

By coupling PUE like grinders, de-shellers, cold storage, egg incubation, etc., with the agrivoltaics, there is strong potential to enhance both income opportunities and downstream impact of the agrivoltaics.

Socioeconomic development outcomes, particularly for nutrition and gender

Agrivoltaics offers critical entry points for advancing gender mainstreaming. Agrivoltaics can also be paired with school lunch programs and other initiatives to help bolster local nutrition efforts.

Improve viability of mini-grid models

Provides a high-visibility project that improves community buy-in for mini-grids, creates stable energy consumption and revenue through PUE, and provides a foundation for additional community and development partner collaboration.

Figure 16. Overview of agrivoltaic benefits for mini-grid contexts[208]

Agrivoltaics can expand local agricultural production, especially staples like beans, groundnuts, and potatoes, as well as high-value items like tomatoes, garlic, chilies, and livestock (especially chicks), by improving yields through formalized agriculture (and directly through the agrivoltaic microclimates in some cases), reducing post-harvest losses through cold storage, and improving livestock production. As highlighted previously, this can help increase

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[208] Illustration by Christopher Schwing, NREL

availability of and access to local agricultural production in local markets as well as through food security efforts like school/church lunches.

Agrivoltaics can strengthen local economies and income opportunities, particularly for local farming cooperatives/associations by providing access to PUE equipment to expand productivity, create value added products (e.g., mamba), offer expanded fee-for-service models to the community, etc. Further, the PUE applications can help to reduce physical and time burdens associated with tasks like water collection, grinding, and shelling, both directly for the agrivoltaic partners as well as potentially for the broader community through the fee-for-service model, thereby unlocking time for other activities.

Agrivoltaics can reduce the competition for land between energy access and agriculture. This is a powerful benefit that can help secure community buy-in and help mitigate potential negative impacts from mini-grid development. Stakeholders highlighted land acquisition and the environmental and social impact assessment process as areas of key concern for mini-grid development. In Haiti, for example, mini-grids in the PHARES program must comply with specific environmental and social impact assessment requirements to secure concessions/licenses from the government as well as incentive funding and support from development partners like USAID, World Bank, and the Inter-American Development Bank. All stakeholders interviewed highlighted that impacts on land (and the existing social uses of that land) were one of the biggest potential negative impacts[209] for mini-grids. Agrivoltaics can help to substantially mitigate these impacts and potentially enable more productive agriculture than the baseline as well.

All of this can help improve the viability of mini-grid models. By providing both energy access and agricultural production (especially when partnering directly with local cooperatives), agrivoltaics can improve community buy-in, which is essential for the long-term sustainability and viability of the mini-grid model. As highlighted previously, agrivoltaics can also help reduce challenges for environmental and social impact assessments for mini-grids, which can potentially reduce administrative timelines and unlock critical incentive financing. Further, the PUE applications can be a small, but secure and meaningful, off-taker load and revenue source for the mini-grids. The simple PUE business/collaboration models for agrivoltaics can also lay the foundation for supporting more ambitious PUE like water pumping/treatment. Agrivoltaics presents a high-visibility and high-impact opportunity for mini-grid developers, which can help build awareness, collaboration, and support among development partners, the government, and other communities—all of which can help enhance the mini-grid business model.

Agrivoltaics, can help advance parallel development goals, particularly for gender. Agrivoltaics projects have key potential entry points for gender mainstreaming. For example, stakeholders highlighted that mini-grid developers can directly partner with women's cooperatives/associations for the operation of the agrivoltaics site, including for crop/livestock production, PUE, sales, and overall governance. Not only would this provide potential income/revenue from the agricultural sales, but the partnership could also help to address existing inequalities and barriers for women in the agricultural sector, including limited access to quality land, inputs and tools for improved productivity, capacity building, appliances and mechanization for agricultural processing, and decision-making power.

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[209] Other key impacts included solid waste and electronic waste management.

7.2 Relevance to Other Contexts

While this work largely focused on evaluating agrivoltaics for mini-grids in Haiti, many of the findings and key considerations are relevant and either directly applicable or adaptable to other geographies and distributed solar contexts (e.g., utility-scale solar and stand-alone distributed solar). In general, any agrivoltaic project should consider many of the same factors that are evaluated in this report, and therefore the framework developed in this report is meant to be flexible and adaptable.

For example, the specific crop and livestock selection may need to be adjusted (though many of the identified crops are grown globally), but the archetypes and framework for selection outlined previously could easily be applied to other contexts. Further, the engineering design may need to be adjusted to local norms or standards, and shading, solar irradiation, and potential electricity output would need to leverage inputs appropriate to the context, however the same approach would generally apply. PUE appliances would need to align with new crop/livestock selections and water needs, but the modeling considerations would likely still be relevant. Business models for agrivoltaics would broadly consider the same high-level factors, and there is still a critical need for any agrivoltaics project to focus extensively on partnerships, capacity building, and community engagement to ensure effective outcomes and long-term viability. Finally, gender entry points would need to be tailored to specific context/challenges, but it is likely that the same entry points would exist in some capacity, particularly with regards to project design, partnerships, agricultural production/processing, training, and workforce development.

7.3 Other Considerations

The PUE applications highlighted in this analysis are meant to be illustrative and were selected for a variety of reasons, including alignment with identified crop/livestock mix as well as the overall perceived ease of implementation, complexity, and costs, as stakeholders consistently highlighted that agrivoltaics would have a much higher chance of success if it did not create additional complexity or implementation risk for the already challenging mini-grid models. A key aspect of potential agrivoltaics pilots will be working with stakeholders to identify and develop appropriate PUE applications, balancing factors like agricultural value chains, appliance availability, integration into mini-grids, etc.

For example, for crop production, crop drying was flagged by stakeholders as a potentially important PUE application, particularly for fruit value chains, corn, and beans. Similarly, other PUE equipment like threshers, hullers, de-kernelers, etc., were also highlighted. Some of these applications could work within an agrivoltaics project, but it is important to highlight that some of these applications may be more relevant for crop varietals that are less compatible with agrivoltaics. Fruit production, for example, is not likely to be directly compatible with agrivoltaics because fruit trees can shade mini-grid panels and reduce electricity output. For crop drying more generally, active and passive crop drying have been shown to provide significant value for agricultural value chains in emerging markets but can be complicated to set up and very context-dependent, so were not modeled.[210,211,212,213]

Other crops like coffee and cocoa could potentially be integrated into agrivoltaics and provide strong revenue potential but would have extensive need for more precise and complex PUE setups, both upstream for processing, and also for packaging. On the livestock side, there could be potential for applications like milking machines, milk chillers, or cheese-making operations. As highlighted in Section 4.7 Water, pumping and irrigation were also highlighted as key areas of interest. Stakeholders also highlighted that centralized PUE models like those demonstrated through an agrivoltaic application could potentially build structure and highlight pathways for broader collaboration on PUE.

7.4 Key Risks

In addition to the considerations highlighted in the previous subsections, there are several key risks for agrivoltaics projects:

Country instability and security: Agrivoltaic projects should proactively navigate the security situation and potential impacts in the country. Logistics and transportation can particularly be impacted by several disruptions like gang activity, protests, road closures, landslides/flooding, etc., which can increase costs, transit times, and availability of goods (e.g., agricultural inputs, tools, etc.) at a minimum, but especially in more isolated rural communities can also lead to full closures of market days. This both highlights the importance of developing local agriculture and also presents a risk for downstream sales of agricultural products. Working closely with the mini-grid community as well as the broader network of communities, farmers, nongovernmental organizations, etc., can help manage these risks to the extent possible, but any agrivoltaic project in Haiti will need to factor additional time and money into its operations and remain flexible to adapt to the dynamic socio-political circumstances in Haiti.

Agricultural yields: Especially in Haiti, agrivoltaic projects face similar risks to the broader agriculture sector where crop/livestock productivity can be negatively impacted by a variety of factors like climate change, natural disasters, droughts, pests, lack of inputs, etc. It therefore can be important to diversify operations and not rely on single crop varietals or value chains. Further, lack of agrivoltaic crop production data in Haiti presents uncertainty around the impact of the agrivoltaics on local crop yields. Collaborating farmers should be aware of these potential yield impacts. As agrivoltaic projects are developed in Haiti, primary data collection will help to reduce these uncertainties around yield impacts.

Electricity reliability and PUE equipment: Maintaining electricity uptime and reliability of service is a key challenge for mini-grid operators in Haiti, especially with the current country security situation and fuel shortages. If agrivoltaics projects are developing business models with tight margins based on the use of electricity, any disruptions to that service can create significant risks for the project. While general agricultural production on-site could continue if the

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[210] Udomkun, Patchimaporn, et al. 2020. "Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach." *Journal of Environmental Management* 268. https://www.sciencedirect.com/science/article/pii/S0301479720306629.

[211] Fudholi, A., et al. 2010. "Review of solar dryers for agricultural and marine products." *Renewable and Sustainable Energy Reviews* 14. https://www.sciencedirect.com/science/article/pii/S1364032109001567.

[212] Boroze, Tchamye, et al. 2014. "Inventory and comparative characteristics of dryers used in the sub-Saharan zone: Criteria influencing dryer choice." *Renewable and Sustainable Energy Reviews*. https://www.sciencedirect.com/science/article/pii/S1364032114005103.

[213] Ndukwu, M.C., L. Bennamoun, and F.I. Abam. 2018. "Experience of Solar Drying in Africa: Presentation of Designs, Operations, and Models." *Food Engineering Reviews* 10. https://link.springer.com/article/10.1007/s12393-018-9181-2.

grid was offline, the use of PUE equipment would need to be curtailed if there was no available power. Depending on the length of the outage, this can result in missed revenue from processing or other PUE, as well as potential spoilage or losses due to interruptions of cold storage, particularly for animal products. A similar dynamic can occur if the PUE equipment itself breaks down. While it is being repaired or replacement parts sourced, revenue potential from PUE is curtailed. This highlights the importance of sourcing and maintaining spare parts for both the mini-grid and the PUE equipment, maximizing the contribution of solar energy and storage, and ensuring local operations staff can support with at least basic repairs and replacements.

PUE demand: As was highlighted in Section 4.6 PUE, the viability of the PUE value streams and justification for investment in the equipment is contingent on ensuring that demand and throughput for the PUE equipment is available. Oversizing the PUE equipment or misestimating demand or utilization can create significant revenue and recovery risks for the mini-grid developer and local cooperatives. Accordingly, specific partnerships with local cooperatives and extensive community engagement are needed to help refine estimates for PUE need and identify appropriate solutions.

Cost uncertainties: As highlighted throughout, costs are a significant uncertainty for developing agrivoltaics in Haiti. Estimates from studies, including this one, should not be used for final decision-making on agrivoltaics projects in Haiti.

Gender: Implementing an agrivoltaics project that does not proactively work to incorporate gender into its design and implementation (see key potential entry points in Section 4.12 Gender above) has the potential to reinforce gender inequalities and the structures that enable them.

Recovery risk: A significant risk for the overall mini-grid business models is that generally the mini-grid developer must pay for equipment and other items upfront in dollars but must recover value over time from collecting HTG from local communities. With the volatility of the currency and country, this creates a significant risk for mini-grid business models and timelines. The same is true for agrivoltaics, as upfront purchases like PUE equipment and the integration of agrivoltaics into the mini-grid itself will be made in dollars, but downstream revenue from sales or PUE utilization will be in HTG. It is important therefore to build contingency funding into projects to help manage the risk.

7.5 Recommendations

Learn by doing. A common highlight from stakeholders and a repeated finding throughout the analysis was the need to develop a pilot project for agrivoltaics to test and demonstrate the potential in Haiti. Stakeholders across the spectrum expressed clear interest in the potential concept of agrivoltaics and stressed that a demonstration pilot that prioritized learning (what does not work is as important as what does), refining and testing key assumptions, and identifying key unknowns was the most direct way to advance agrivoltaics in Haiti.

Start simple. Mini-grids are already a complex business model and solution, especially in the context of the socio-political challenges and operating environment in Haiti. While agrivoltaics certainly can be a wide-reaching and expansive solution, it is critical for first pilots to explore simple configurations that can be deployed without adding significant operational complexity, costs, or implementation risk for developers and their partners. Simple configurations can be used to prioritize learning outcomes for elements like agricultural production, costs, business/collaboration models, community engagement, etc., and to lay a foundation for more complex elements to be added later.

Prioritize co-development and capacity building. The key enabling factor for agrivoltaics is community engagement and partnerships, particularly with local cooperatives/associations. Deep, intentional engagement will ensure that agrivoltaic outcomes are community-oriented, technically sound, and economically viable. Developers and other partners should identify and involve these groups early on in project scoping to enable co-development of agrivoltaic solutions right from the start. The partnership also needs to have a deliberate focus on capacity building and training, not just for technical aspects, but also for financial/managerial elements, value chains, mini-grids, safety, etc. To truly sustain impact, capacity building cannot be a one-off approach, but should instead be designed to provide systematic, longer-term support, including refresher training and on-site supervised learning.

Purposeful integration of gender. Agrivoltaics, if intentionally designed, can support gender mainstreaming and equity outcomes for local communities in Haiti. Without integration of gender, however, agrivoltaics can exacerbate existing inequalities. An important starting point is identifying and partnering with local women's groups, as they can help identify and unlock other entry points for gender mainstreaming, particularly for community engagement, training, workforce development, and agricultural production.

Enable patient and flexible support. Agrivoltaics is complex and will require a flexible and patient approach to design and implement. Given the current socio-political challenges, it is likely that any pilot project will need to dynamically adapt to changing circumstances, which will require patient and flexible timelines, support, and finance from partners and funders to enable key pivots or workarounds.

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