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Renewable Electricity Technologies to Increase the Resilience of the Food Supply System in Puerto Rico

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Introduction

This paper describes the challenges and potential opportunities for using renewable electricity technologies to increase the resilience of Puerto Rico's food supply system (including commodity production, processing, storage, and distribution) to prolonged (2 days to 6 months) utility power outages. This need is essential because the island's grid electricity has proven to be very susceptible to long-run outages related to severe weather and geologic events (e.g., Hurricanes Irma and Maria in 2017 and earthquakes in 2019 and 2020) as well as outages related to aging and poorly maintained infrastructure. Hurricane Maria destroyed more than 80 percent of Puerto Rico's crop value, with infrastructure damages of $1.8 billion in Puerto Rico's agricultural sector (PR DOH, 2019, p. 83; USDA, 2018).

As background for this paper, ICF held a series of discussions with officials in Puerto Rico with expertise in the island's food supply. These experts include U.S. Department of Agriculture (USDA) staff in Puerto Rico serving the Caribbean Climate Hub, Rural Development (RD), and Natural Resources Conservation Service (NRCS) programs and representatives from agricultural trade groups and academia (see Appendix). Across these conversations, there was general consensus on the following points. First, Puerto Rico's future economic growth, including the success of agriculture and the food supply system, depends on improving the stability and resilience of electricity supply. Second, achieving this stability and resilience will require investing in electricity systems that are designed and built to endure major disruptions, contain impacts when disruptions do occur, recover quickly, and deliver adequate power quality throughout the year. Third, investments in Puerto Rico's electricity supply should emphasize keeping costs predictable and manageable; maximizing use of local resources to reduce dependence on imported oil and liquified natural gas; and facilitating environmental improvements. Finally, there was a recognition that Puerto Rico's electricity infrastructure is outdated and not well maintained. While a new electric utility governance framework is under consideration, progress has been slowed by its projected cost of up to $20 billion and long-run declining electricity demand on the island due to depopulation.

Because renewable technologies can play an important role in enhancing the stability and resilience of electricity supply in Puerto Rico, particularly in rural areas and for industries in the food system, USDA's Office of Energy and Environmental Policy (in the Office of the Chief Economist) and ICF collaborated to produce this paper. It is organized as follows:

- Puerto Rico Electricity Profile
- Critical Power Needs of Food Supply Sectors
- Renewable Electricity Technologies to Increase Resilience
- Conclusion: Implementing Resilient Renewable Electricity

Though the descriptions and examples in the paper cover a range of agricultural production and food supply activities in Puerto Rico, the term *food supply system* is used to cover all activities collectively.

Profile of Electricity in Puerto Rico

Agricultural sector electricity needs operate against the backdrop of the electric grid in Puerto Rico. The grid is operated by the Puerto Rico Electric Power Authority (PREPA), which is a government-owned utility.

RESILIENCE CHALLENGES

PREPA, which had $9 billion in debt when it declared bankruptcy in 2017, has historically struggled to maintain its grid. The median age of PREPA's power plants was 44 years, compared to a U.S. industry average of 18 years at that time (PREPA, 2017, p. 10). Even before the 2017 hurricanes, the frequency of utility power outages was "an order of magnitude higher than the U.S. average" (DOE, 2018a, p. 13). Beyond aging infrastructure, PREPA's system has several features that reduce resilience, including (i) its status as an island system that lacks interconnection with neighboring systems for stability, (ii) reliance on overhead lines on its distribution system that are challenged to withstand strong hurricanes, (iii) the need to "traverse mountainous, densely vegetated terrain" to move power from where it is primarily generated (southern portion of the island) to San Juan in the north, and (iv) the lack of a transmission load flow model (PREPA, 2019, p. 34). In addition, almost 40 percent of PREPA's workforce, primarily skilled generation, transmission, and distribution operations staff, have left since 2008 (PREPA, 2019, p. 30; DOE, 2018a, p. 40).

In 2017, Hurricanes Irma and Maria damaged or destroyed 80 percent of the island's transmission and distribution power lines (EIA, 2019). The largest power generation facilities were operational within weeks after Hurricane Maria, but they could not supply power until the utility's transmission and distribution networks were repaired (Gallucci, 2018).[1]

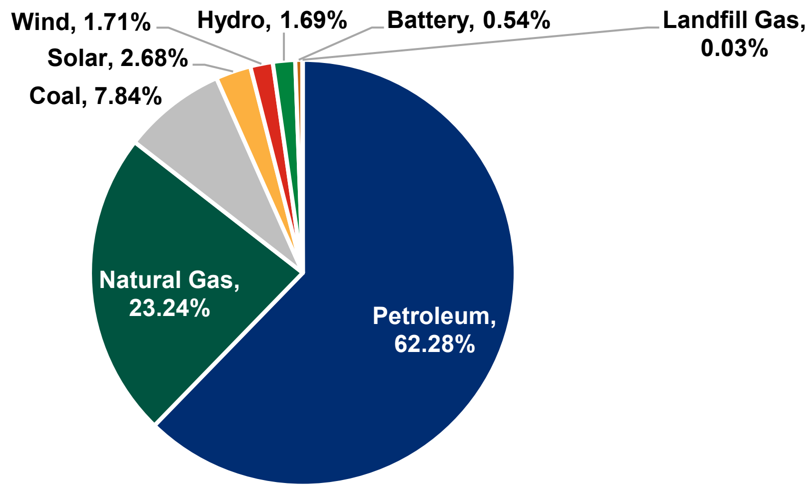
Hurricane Maria caused the longest power outage in U.S. history, as parts of Puerto Rico remained without electricity for 328 days (Government of Puerto Rico et al., n.d., p. 2). A significant modernization plan for the PREPA system is being considered, but it is estimated to cost up to $20 billion and take 10 years to implement (Government of Puerto Rico, et al., n.d., p. 9).

PRESENT ELECTRICITY GENERATION SOURCES

Power supply in Puerto Rico is largely dependent on fossil fuels, with renewable sources only accounting for about 7 percent of utility-scale generating capacity as shown in *Exhibit 1*.[2]

[1] "Transmission networks consist of high-voltage power lines designed to carry power efficiently over long distances. Distribution networks deliver power at lower voltages and over shorter distances to the consumer" (EPA, 2019, p. 2). Vertically-integrated utilities like PREPA operate both transmission and distribution networks.
[2] These data are for net summer capacity and do not include distributed generation systems. Total net summer capacity as of February 2020 was 5,791 megawatts (MW) (EIA, 2020a).

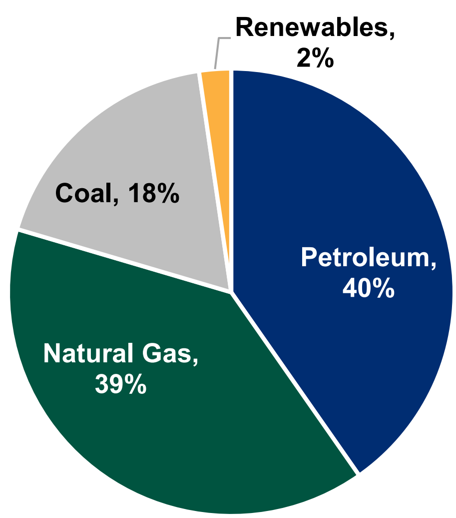
EXHIBIT 1: Puerto Rico Utility-Scale Electricity Generation Capacity by Source



Source: Based on U.S. Energy Information Administration: EIA, 2020a.

While *Exhibit 1* shows the ***capacity*** of utility-scale generating units on the island, it is also useful to review **annual electricity production** in *Exhibit 2*.

EXHIBIT 2: Puerto Rico Electricity Production by Source



Source: Based on U.S. Energy Information Administration: EIA, 2020b.

Because renewable sources like wind and solar are intermittent (since the amount of available wind and sunlight varies throughout the day and year), they tend to produce at or near peak capacity less often than fossil fuel power plants. That is why renewable sources account for only 2.3 percent of electricity production, but a larger share of generating capacity (EIA, 2020b).[3] In comparison, more than 17 percent of total U.S. utility-scale electricity production is from renewable sources, including 7 percent from hydropower (EIA, 2020c). The fossil fuel-dependent generation mix of Puerto Rico also results in high greenhouse gas (GHG) emissions rates on the island.

Due to PREPA's heavy reliance on imported petroleum and imported liquified natural gas, Puerto Rican electricity prices fluctuate along with international fossil fuel prices and are higher than those of every State in the continental United States. Electricity in Puerto Rico costs more than twice the U.S. average, with residential and commercial customer electricity prices as of early 2020 being $0.27/kilowatt-hour (kWh) and $0.30/kWh, respectively, on the island compared to $0.13/kWh and $0.10/kWh across the U.S. (EIA, 2020b).

PLANS FOR MORE RENEWABLE GENERATION

Regulation 9021 of the Puerto Rico Energy Transformation and RELIEF Act was adopted in 2018 and requires that PREPA develop an Integrated Resource Plan (IRP). The IRP aims to provide transparency into electricity planning, optimize resource cost-effectiveness, and meet environmental regulations (Siemens, 2019, p. 2-3). One IRP scenario included in PREPA's 2019 fiscal plan forecasts that in the next 4 years, Puerto Rico's annual electricity production would be generated with a mix of 35 percent renewables, 35 percent natural gas, 21 percent coal, and 9 percent petroleum (PREPA, 2019, p. 21).

For the longer term, Puerto Rico's new energy public policy includes a minimum of 40 percent renewable electricity on or before 2025; 60 percent on or before 2040; and 100 percent on or before 2050 (SB 1121, 2019). This transition to 100 percent renewable electricity is envisioned to leverage both centrally located, utility-scale units to serve island-wide needs and smaller scale distributed generation, particularly solar photovoltaic (PV) and battery storage, at individual households and businesses (SB 1121, 2019; RPRAC, 2018, p. A28).[4]

In pursuing more renewable power on the island, the greatest commercially available potential is from solar and wind resources as shown in *Exhibit 3*.[5]

[3] Renewable energy sources are grouped together in *Exhibit 2*, as opposed to the break-out by renewable energy technology in *Exhibit 1*.
[4] As of mid-2017, there were 88 MW of distributed generation on the island (RPRAC, 2018, p. A25).
[5] Ocean energy production, which involves a nascent technology, is not included in this table. The National Renewable Energy Laboratory (NREL) notes high potential for it (NREL, 2015, p. 3).

EXHIBIT 3: Puerto Rico's Renewable Energy Potential

Resource	Potential Generating Capacity (MW)
Solar	1,100
Wind	840
Biomass	290 to 6,800[6]
Hydropower	103
Geothermal	Unknown, likely very low

Source: National Renewable Energy Laboratory: NREL, 2015, p. 3.

Critical Power Needs of Puerto Rico's Food Supply Sectors

In Puerto Rico as of 2018, there were approximately 8,200 agricultural farms generating $485 million in annual agricultural product sales, with additional economic activity occurring across the island's food supply chain (USDA, 2020a, p. 16).[7]

Prior to the 2017 hurricanes, on-island production accounted for 15 percent of Puerto Rico's food supply (USDA, 2015). In the aftermath of the hurricanes, that figure declined to 5 percent (FAO, 2018). From the hurricanes, "crops were decimated by wind and flooding, mudslides in the mountainous interior took out many of the roads critical to agricultural production," and substantial livestock was lost (PR DOH, 2019, p. 83). The significant impact of the storms can also be seen in differences between 2012 and 2018 in key capital and labor inputs to agriculture in Puerto Rico: the aggregate market value of land and buildings decreased by more than $1 billion, while the aggregate value of machinery and equipment increased by approximately $70 million and per-farm labor costs increased as farms sought to rebuild and recover (USDA, 2020a, pp. 13-14).

Before considering electricity resilience options, it is important to carefully define the problems. For Puerto Rico's food supply activities -- growing food as well as processing, storing, and distributing food on the island – the problems of unreliable power do not equally affect all parts of the industry or all electricity uses.

In this section, critical vs. non-critical power needs are distinguished, types of food supply businesses with especially high dependence on electricity resilience are highlighted, and future electricity vulnerabilities for food supply firms are summarized.

DEFINITION OF CRITICAL VERSUS NON-CRITICAL ELECTRICITY USES

Critical electricity uses are those for which interruptions result in lost business or production capacity, idled workforce, loss of product, damaged equipment, and compromised health and safety (Schneider Electric, 2015). It is important that critical uses continue to have uninterrupted power, even during grid outages.

In the context of food supply, refrigeration for perishable foods, water pumping for livestock operations, and power uses that ensure the safety of humans, animals, and valuable assets can be considered ***critical electricity uses***. Non-critical electricity uses are those that enhance or

[6] "The lower limit is traditional agricultural biomass, and the upper limit assumes that microalgae is commercially viable and in widespread use at maximum capacity" (NREL, 2015, p. 3).
[7] The number of farms in Puerto Rico in 2012 *Census of Agriculture* data was much higher, at more than 13,000. The value of agricultural products sold by Puerto Rico farms was also higher in 2012, at almost $550 million (USDA, 2020a, p. 16).

facilitate operations, but whose constant availability is not necessary to maintain the ongoing functions of the business. Examples of ***non-critical electricity uses*** in agriculture could be air conditioning, lighting for offices, and maintenance equipment.

FOOD SUPPLY ACTIVITIES WITH SIGNIFICANT CRITICAL POWER NEEDS

Our background discussions with USDA officials, trade association representatives, and agricultural experts in academia highlighted several critical power requirements in Puerto Rico's food system. Much of Puerto Rico's food production for local consumption is perishable, thus heightened electricity resilience is needed in many parts of the food system. Across all agricultural commodities in Puerto Rico, milk and other dairy have the highest annual sales at $172 million, followed by grains or field crops; plantains; cattle; nursery and greenhouse crops; vegetables and melons including hydroponic crops; and poultry (USDA, 2020a, p. 16).

The most commonly cited critical power need is in the ***dairy*** sector, which is Puerto Rico's largest livestock sector. On a gross income basis, the dairy sector comprises 62 percent of the island's livestock industries (Ortiz-Colón, 2018, p. 3). The dairy sector lost 55 percent of its production at the farm after the 2017 hurricanes, and incurred significant losses throughout the entire supply chain due to damaged business assets and transportation infrastructure, electricity outages, and purchase program closures (Ortiz-Colón, 2018, pp. 16-17).[8] Four months after the hurricanes ended, 60 percent of dairy farmers still did not have utility power (Ortiz-Colón, 2018, p. 21). Without power, many had to use emergency diesel generators, which tripled their energy costs (Ortiz-Colón, 2018, p. 21). The dairy sector's incidence of critical electricity use is high due to regular milking demands and the need for refrigeration. Even short lapses in power supply can lead to spoiled milk or endanger cow health when cows cannot be milked on a regular schedule.

Another critical power use in Puerto Rico's livestock sector is in ***poultry*** operations. They require cooling fans due to the high-density, confined nature of their facilities and the island's high year-round temperatures. Because poultry farms can be exposed to high animal mortality during multi-day outages, cooling is a critical use. On a relative basis, poultry and egg farms are more likely to implement solar energy technologies than other types of farms in Puerto Rico (USDA, 2020a, pp. 117-118).

In the ***coffee*** industry, processing plants have a critical power use because coffee beans must be dried within a short time of being picked to avoid degradation. Coffee processing facilities tend to be in the mountains, near coffee farms, where they are exposed to more frequent electricity outages than facilities in coastal parts of the island. Other agricultural activities in mountain areas face similar power shortfalls, as the high concentration of the island's population and power plants in coastal areas often leads to faster power restoration on the coasts than inland areas.

Food intermediaries must keep produce and animal products refrigerated during packing and distribution processes to maintain freshness and avoid spoilage. For these firms, refrigeration is a critical electricity use, as prolonged outages result in considerable losses.

Due to the frequency of PREPA power outages affecting agricultural activities, there has already been a ***trend, starting long before the 2017 hurricanes, toward the installation of on-site, back-up diesel generators*** to provide emergency power at farms and food processing facilities. As the cost of renewable power has decreased in recent years, deployment of renewable back-up

[8] 4,200 cows were lost due to the 2017 hurricanes (PR DOH, 2019, p. 83).

power systems and hybrid renewable-diesel systems has increased, though diesel-only systems remain the most common solution.

ELECTRICITY VULNERABILITIES

Puerto Rico is especially vulnerable to disruptions in its food system, due to several factors:

- Heavy reliance on food imports (85 percent of the food it consumes is imported[9], with that figure rising to 95 percent after the 2017 hurricanes) (FAO, 2018)
- Use of a single seaport in San Juan for most food imports
- Exposure of many critical domestic food system components to outages in grid-supplied electricity (Port Authority, 2017, p. 4)

Going forward, the island is likely to face continued major risks to its electricity grid due to hurricanes, earthquakes, cybersecurity issues, and the condition of its grid infrastructure. According to the most recent National Climate Assessment, intense tropical cyclones -- such as Category 4 and 5 ***hurricanes*** – are likely to affect Puerto Rico with increased frequency over the course of the 21st century (U.S. Global Change Research Program, 2017, Chapter 9). Puerto Rico is also at long-term risk of damaging ***earthquakes***, given the island's location at the boundary between the Caribbean and North American tectonic plates. The island's ongoing earthquake hazard is approximately on par with much of the U.S. West Coast (Pagani, et al., 2018; Mueller, et al., 2010). As demonstrated by earthquakes in southwest Puerto Rico in late 2019 and early 2020, future earthquakes have the potential to result in long-term power outages.

Lastly, PREPA's ***aging infrastructure*** magnifies its susceptibility to (i) major outages related to natural hazard events, and (ii) additional outages related to failures of degraded system components. In a regulatory proceeding, PREPA described an "ailing grid," "degraded infrastructure," and a "deteriorated" transmission system (DOE, 2018a, p. 12). While additional investments have been proposed for the PREPA electric grid, these plans have yet to be approved. After approval, implementation would take 10 years (Government of Puerto Rico, et al., n.d., p. 9).[10] Furthermore, the utility's long-term plan foresees agricultural electricity consumption from the grid continuing to decrease for the next 18 years, due largely to depopulation and its effects on island economic growth (Siemens, 2019, p. 3-10).

Given the vulnerabilities described above, it is worth considering the ways in which renewable electricity technologies might increase the resilience of Puerto Rico's electricity supply.

Renewable Electricity Technologies to Increase Resilience

This section summarizes the operation and cost of wind, solar, and biomass renewable electricity systems that may be available to farms, firms in other parts of the food system, and rural communities in Puerto Rico.

[9] Puerto Rico's food imports come from 52 countries, with about 80 percent of the food import shipping originating from the port in Jacksonville, Florida (USDA, 2015).
[10] Puerto Rico's electricity grid also faces risks of long-term power outages from cyber attacks, like other U.S. power grids. These risks increase the importance of resilience for critical power needs nationally. The deployment of more advanced technologies on grids may provide more avenues for power outages. Specifically, "interoperable technologies created for a shift toward a smart grid will continue to expand the cyber attack landscape" (INL, 2016, p. ii).

Renewable electricity systems can, depending on their configuration, increase resilience by supplying electricity when utility grid outages occur. The modes of operation in which they are configured, as well as resource availability and system size, determine the amount and duration of back-up power that can be provided. Battery energy storage technologies can be paired with solar and wind systems to improve resilience against power outages.

Beyond resilience, renewable electricity systems can have the co-benefits of decreasing Puerto Rico's reliance on fuel imports and reducing GHG emissions. In many cases, renewable systems also decrease annual electricity costs for food supply businesses.

MODES OF OPERATION FOR ON-SITE ELECTRICITY GENERATION

Renewable electricity systems, whether serving an individual facility (e.g., a farm or food processor), a group of facilities (e.g., a farmer cooperative), or an entire rural community can be described as operating in "parallel" with the electric grid or "islanded" from it.[11]

Two Modes of Operation

In ***parallel*** systems, facilities are simultaneously connected to the on-site electricity generation system and the utility's electricity grid. This allows end-use customers to draw power from the grid when the renewable electricity system is producing less electricity than needed on-site, and to feed power back into the grid when on-site generation is producing more electricity than is needed. As typically designed, parallel systems will <u>not</u> provide power when the grid is offline because these systems include a component that shuts off the renewable energy system within milliseconds of the grid losing power. This feature prevents renewable electricity systems from feeding power into the grid and endangering people working on or around powerlines (e.g., line workers and firefighters) that need repair in the restoration process. This feature also prevents damage to customer equipment that cannot withstand variability in electricity production associated with intermittent resources like solar and wind.

In ***islanded*** systems, power from the electricity generation system can be safely generated and used by the end-use customer in the absence of connection to an operating utility grid. For example, farms may use "off-grid" renewable systems serving agricultural uses without ready access to grid power, such as lighting remote structures, water pumping and irrigation, pond aeration, and remote communications (USDA, 2011, pp. 11-15).

On-grid systems can also operate in islanded mode if configured for dual modes (parallel and islanded). Such dual-mode systems disconnect from the utility system and run in islanded mode when needed (e.g., during grid outages). Such systems can then be safely reconnected to the utility system once power is restored on the grid.

From the standpoint of improving resilience in Puerto Rico's electricity supply, islanded systems, whether configured to be on-grid or off-grid, are necessary for maintaining power to critical uses during outages (such as milking cows, chilling milk, cooling poultry, and drying coffee).

Microgrid Operations and Examples

Renewable electricity generation systems, with or without battery storage, can also be linked into "microgrids." In on-grid configurations, microgrids are interconnected sets of generation sources

[11] Parallel mode is also called "grid-connected" mode.

and electricity consumption loads within defined electrical boundaries that can operate as a single electrical entity in parallel (to the utility grid) and islanded modes and transition between those modes.[12] Off-grid microgrids are similar except, by definition, operate exclusively in islanded mode and do not have a connection to the utility grid.

There are renewable microgrids designed to serve a single organization; these may integrate PV or wind, a battery energy storage system, and possibly a diesel generator to serve one or more buildings with the same owner. For islanded mode operation, these ***"customer microgrids"*** may be sized with enough electricity generation to serve all of the customer's (critical plus non-critical) power needs, or only its critical power needs. For example, ten microgrids using PV and battery energy storage were installed to serve critical power needs at schools in mountainous areas of Puerto Rico (RMI, 2019).

There are also ***"community microgrids"*** that can serve large numbers of community members. For example, there are community microgrids in rural areas like those funded by USDA's High Energy Cost Grants program in Alaska.[13,14]

Microgrids can be particularly beneficial in Puerto Rico given the aging and under-maintained condition of the centralized utility grid, the rugged terrain in much of the island that makes power delivery and restoration difficult, and the island's vulnerability to hurricanes and earthquakes that cause grid outages. A Puerto Rico regulation was approved in 2018 to assist in the development of microgrids throughout the island (PREB, 2018). Microgrids, however, can be costly and require careful planning to be built, maintained, and operated effectively.

RENEWABLE TECHNOLOGY DESCRIPTIONS

Solar Energy

In both the U.S. generally, and in Puerto Rico in particular, no renewable electricity generation technology has experienced more rapid growth over the past decade than PV. Deployment of this technology, which converts sunlight into electricity, at commercial, industrial, and residential scale[15] grew by 216 percent between 2014 and 2019 in the U.S. (EIA, 2020d).[16] USDA supported deployment of nine PV systems in Puerto Rico in 2019, with grants of $5,000 to $20,000 to each system (USDA, 2019b, p. 15). These grants, under the Rural Energy for America Program, are all projected to create large financial savings and, in one case, include a combined PV and battery storage system (Caribbean Business, 2019).

PV is a mature technology that can be readily installed on numerous sites at farms, other food supply businesses, and rural households, including rooftops, flat ground surfaces, and parking

[12] For more information on microgrids, see DOE 2012 and DOE, 2020.
[13] This USDA program awarded a grant of $1.3 million in 2019 to the Northwest Arctic Borough in Alaska to develop a solar and battery storage system connecting to the community's existing diesel generator and electric distribution system (NAB, 2019; USDA, 2019a). In addition to environmental benefits, adding solar and a battery system is expected to lower electricity costs (NAB, 2019).
[14] An example of a community microgrid, with an agricultural emphasis, was deployed in Haiti. The solar-diesel hybrid microgrid increased access to affordable, reliable electricity for value-added agricultural processing (Powering Agriculture, n.d.). The microgrid expanded from a pilot stage with 54 connections to a town-sized grid offering electricity to residential and business customers through 452 connections (Powering Agriculture, n.d.). In Afghanistan, a rural, off-grid microgrid provides electricity using a combination of PV and lead-acid battery systems, with diesel generators for back-up power supply (USAID, 2018).
[15] Commercial-, industrial-, and residential-scale applications of PV are those relevant to food supply activities and are called "small-scale" by EIA, to distinguish them from larger, "utility-scale" applications.
[16] Small-scale PV capacity grew by more than 3,000 MW nationally in 2018 and again in 2019 (EIA, 2020d).

canopies. Among ground-mounted PV systems, there is increasing interest in low-impact site development plans. Such plans differ from traditional PV development plans in their attention to preserving topsoil and planting vegetation that is conducive to pollinators and other insects favorable to agriculture at nearby farms (NREL, 2019). Off-grid applications for agricultural activities that do not receive power from a utility are a smaller part of the PV market than on-grid applications; however, the agricultural sector has played a strong role in the off-grid PV market, and off-grid systems can be a cost effective solution for remote applications (USDA, 2011, pp. 11-15).

Solar is the most widely-adopted renewable energy technology among farms in Puerto Rico at 73 percent of all renewable systems, as shown in *Exhibit 4*.

EXHIBIT 4: Puerto Rico Farms with Renewable Energy Systems[17]

Technology	Number of Farms with Renewable Energy Systems	Percent of Total Renewable Energy Systems on Puerto Farms
Solar	234	73%
Wind	20	6%
Geothermal (Geoexchange Systems)	12	4%
Small Hydropower	12	4%
Methane Digesters	6	2%
Other	36	11%

Source: USDA, 2020a, p. 21.

The popularity of solar among renewable technologies is likely due to its flexibility in sizing, cost effectiveness even at small scale, and wide applicability (e.g., methane digesters require a nearby supply of manure or other wastes).

Wind Energy

While the wind energy industry has grown substantially across the U.S., that growth has been concentrated in utility-scale systems that are far too large for typical use in the food supply industry. The "distributed" wind systems that can be installed on-site at food supply businesses comprise only 1 percent of the national wind energy market on a capacity basis.[18,19] Using individual turbines up to 1,000 kilowatts (kW) in capacity, the distributed wind market's mid-sized and small turbine segments appropriate for food supply businesses had a combined new 2018 capacity of only 3,100 kW (3.1 MW) nationwide (DOE, 2019, p. iv).[20]

While wind is the second most frequently deployed renewable technology among farms in Puerto Rico, it only represents 6 percent of total renewable systems on farms. Nationally, wind energy systems are more common on farms, on a relative basis, than they are in Puerto Rico, with

[17] USDA *Census of Agriculture* data from 2018 record a total of 280 renewable energy systems, though the sum of individual renewable energy technologies exceeds 280, whether due to multi-technology systems or for other reasons (USDA, 2020a, p. 21). The "percent of total" column in the exhibit reflects the sum of individual technology counts.
[18] The cumulative generation capacity of distributed wind projects was 1,127 MW in 2018, compared to approximately 96,000 MW for the overall wind market in the U.S. in 2018 (DOE, 2019, p. 3; AWEA, 2020, p. 5).
[19] Though they are not frequently deployed, distributed wind systems have advantages over ground-mounted PV systems in that they remove less land from direct agricultural use per unit of generating capacity.
[20] 1,000 kW = 1 MW.

approximately 10 percent of renewable energy systems using wind turbines according to the 2017 *Census of Agriculture* (USDA, 2019c, p. 60). [21]

Battery Energy Storage

Battery energy storage systems are becoming increasingly common, both as standalone systems (without being directly linked to an electricity generator) and integrated with PV or wind technologies. The growth of battery storage is relevant to Puerto Rico's food supply sectors because it can expand resilience by storing renewable power produced by PV (and other renewable) systems during grid outages and releasing that power to serve critical power needs when the sun is not shining or when there are power outages.

Rural Electricity Resilience Example: PV + Battery System for Remote Forestry Office in New Mexico

The Cimarron District Forestry Office faced frequent outages and uneven power quality from the utility grid. The office previously relied on a propane generator for back-up power, with propane re-supply risks during extreme weather and wildfire events. To improve resilience and environmental outcomes, the office implemented a combined PV + battery energy storage system. The system operates in parallel mode when grid power is available and immediately switches to serving critical power needs (such as a well water pump and communication systems) in islanded mode during grid outages (CEG, 2020, pp. 5-6).

Image Source: Clean Energy Group: CEG, 2020, p. 18.

Biomass Electricity

Biomass can be used to generate electricity for direct use by food supply businesses. Feedstocks (i.e., fuel) for biomass power generation systems can come from many agricultural and forestry sources such as purpose-grown crops, wood and wood residues, agricultural crop residues, and manure from confined livestock operations. To convert these biomass feedstocks into electricity, the most prevalent technology is direct combustion. Other biomass energy conversion technologies include anaerobic digestion of methane and gasification. Importantly for resilience purposes, and unlike PV and wind energy systems, biomass power generation systems tend to provide predictable "baseload" power that does not change with weather conditions, season, or time of day.[22]

NREL indicates that generating power from traditional agricultural biomass sources has the third-highest potential of all renewable sources on Puerto Rico, after solar and wind (NREL, 2015, p. 3).

[21] The sum of individual renewable energy technologies in the *Census of Agriculture*, rather than that report's smaller total listed for all technologies combined, was used to determine the relative share of wind systems among farms nationally.
[22] The provision of baseload power requires a consistent supply of feedstocks. If feedstocks are disrupted during a power outage (e.g., due to a natural disaster), then the consistent supply of power from a biomass electricity system would likewise be disrupted.

Currently, six methane digesters are reported on the island on hog farms (USDA, 2020a, p. 21). Due to the relatively large size of the dairy industry on Puerto Rico, there may be potential for an increase in the number of methane digesters.[23]

RENEWABLE TECHNOLOGY ECONOMICS

Overview

The economic case for renewable electricity, especially PV, is particularly strong in Puerto Rico. Utility grid power in Puerto Rico is expensive by national standards, with the agricultural sector on the island paying a historical average price of $0.28/kWh and commercial customers paying an average price of $0.30/kWh as of early 2020 (EIA, 2020b; NREL, 2015, p. 2). By comparison, the average U.S. grid electricity price is about $0.10/kWh for commercial customers (EIA, 2020b). That means that renewable systems in Puerto Rico's food supply sectors can have long-term, all-in costs approximately $0.18 to $0.20/kWh higher than in other parts of the U.S. and still have the potential to be profitable investments.

PREPA's "net metering" policies (compensating renewable systems for exporting excess power back to the grid) also support renewable deployment, as does the ample sunlight on the island that increases PV production beyond U.S. averages. Lastly, continued declines in the capital costs of some renewable systems make them more affordable. For example, the cost of commercial-scale PV systems decreased by 66 percent between 2010 and 2018, and lithium-ion battery system costs declined by 74 percent between 2012 and 2018 in inflation-adjusted dollars (GTM Research, 2019; NREL, 2018, p. 27).[24]

System Costs

Renewable electricity systems have two types of costs: capital and operations and maintenance (O&M). ***Capital costs***[25] (also called installation costs) cover initial system deployment, and ***O&M costs*** are paid throughout the system's life to ensure its equipment functions properly and, in the case of a biomass system, that it has a consistent fuel supply.[26] Renewable electricity systems tend to operate for 25 to 30 years, so the initial capital costs are typically amortized, and combined with annual O&M costs, over this expected asset life in long-term investment calculations.

Exhibit 5 contains illustrative capital costs and annual O&M costs for on-grid renewable electricity systems of the scale appropriate for many food supply industry activities.[27] The costs for off-grid systems are not provided by the sources for the exhibit, but on-grid and off-grid systems of the same technology and size should have similar costs.[28] O&M costs typically rise annually with inflation. Capital and O&M costs vary widely in practice based on system size, location, configuration, and local permitting and utility interconnection requirements. The costs shown are

[23] The livestock farms considered to have the best economic potential for anaerobic digestion "are large operations (500 or more head of cow or 2,000 or more head of swine) that use liquid or slurry manure handling systems and collect manure often from animal confinement areas" (EPA, 2018, p. 7).

[24] All of these positive factors apply to on-grid renewable systems, whether or not they can operate in islanded mode. All of the factors, except net metering, also apply to off-grid renewable systems.

[25] Capital costs include the full cost of designing, engineering, constructing, permitting, financing, and purchasing equipment for the system.

[26] For PV and wind energy systems, the fuel is from sunlight and wind and is free. In contrast, for biomass power generation systems, fuel (i.e., feedstocks) can account for up to 50 percent of the lifetime cost of producing electricity (IRENA, 2012, p. 27). In some cases, however, feedstock costs can be negative if the feedstock would incur disposal costs if not combusted.

[27] These costs are from studies published in different years and have not been adjusted to current dollars.

[28] Off-grid systems will not require costs for utility interconnection, but may require additional costs for controls.

before Federal and Puerto Rico-specific financial incentives that lower the lifetime cost of ownership.[29]

EXHIBIT 5: On-Grid Renewable Electricity and Battery System Pre-Incentive Capital and O&M Costs in the U.S.

Technology	Unit Capital Cost in $/kW$_{AC}$ (pre-incentive)	Typical System Size (kW$_{AC}$)	Annual Fixed O&M Cost in $/kW (in year 1 of operation)	Variable O&M Costs
Residential-Scale PV	$3,900 to $4,700	2.7 to 9[30]	$22	N/A
Commercial-Scale PV	$2,600 to $3,500	8.6 to 860[31]	$18	N/A
Distributed Wind – Small Turbines	$5,700 to $8,000	10 to 100	$35	Small cost; data not readily available
Distributed Wind – Mid-Sized Turbines	$2,400 to $5,700	101 to 1,000	$35	
Lithium-Ion Battery Storage	$1,900 to $3,000	250 (with 4-hr. duration)	$29 to $45	Low, until battery must be replaced[32]
Biomass Electricity[33]	$3,000 to $5,000	5,000+	$50	$0.01/kWh (non-fuel) + $0.0145/kWh to $0.029/kWh (fuel)

Sources: Ernest Orlando Lawrence Berkeley National Laboratory: LBNL, 2019, p. 27 (PV capital costs); National Renewable Energy Laboratory: NREL, 2018, pp. 22, 28 (PV O&M costs); National Renewable Energy Laboratory: NREL, 2016, pp. 15-16 (wind); Electric Power Research Institute: EPRI, 2018, pp. 8, 15 (battery); National Institute of Building Sciences: NIBS, 2016 (biomass capital costs); Lazard, 2017, p. 19 (biomass O&M costs).

The levelized cost of energy (LCOE) is a metric of the lifetime costs of generation sources, and it can be compared to the cost of grid electricity. For example, the pre-incentive LCOE of residential- and commercial-scale rooftop PV in the U.S. are estimated at $0.151/kWh to $0.242/kWh and $0.075/kWh to $0.154/kWh, respectively (Lazard, 2019, p. 3). These LCOE are below average residential and commercial electricity prices in Puerto Rico, indicating good potential for savings from PV investments. Despite these favorable long-term economics, the upfront investment required, and lack of ready financing, for PV systems remains a significant deployment barrier in Puerto Rico.

When considering ***microgrid investments***, relevant costs include: (i) capital and O&M for the individual generation or energy storage technologies in the microgrid, (ii) integration of the generation and storage sources with the end-user consumption loads (and interconnection to the

[29] For example, there are Federal investment tax or production tax credits and USDA grant and loan guarantee programs covering all technologies listed in the exhibit. For more information, see NCCETC, 2020; USDA, 2020b; USDA, 2020c; and USDA, 2020d.
[30] PV capital costs and system sizes are converted from direct current (DC) to alternating current (AC) equivalents using the average DC to AC ratio for residential-scale systems with central and string inverters (LBNL, 2019, p. 13).
[31] PV capital costs and system sizes are converted from DC to AC equivalents using the average DC to AC ratio for small commercial-scale systems with central and string inverters (LBNL, 2019, p. 13).
[32] Replacement of the battery itself (part of the battery system) often occurs every seven to 10 years of operation, with the frequency dependent on use patterns. Battery replacement has a significant cost, estimated at about $800 to $1,200/kW for the prototype system in the exhibit (EPRI, 2018, pp. 8, 15).
[33] Biomass system costs are for large systems due to data availability. Smaller systems often have higher unit costs.

utility for on-grid microgrids), and (iii) the microgrid controller hardware and software to manage the microgrid.

MATCHING RENEWABLE TECHNOLOGIES TO FOOD SUPPLY RESILIENCE NEEDS

Different renewable electricity technologies and configurations may be better suited to the needs of a given food supply activity on Puerto Rico. Considerations in selecting the optimal technology and configuration include:

- Resource availability (for sunlight, wind, or biomass)
- System capacity needed and amount of suitable space to install the technology
- Location (including distance to utility power lines and vulnerability to extreme weather and other natural disasters)
- System costs, after applying financial incentives
- Extent of critical and non-critical power needs on-site

For example, areas with significant shading from trees or other buildings will not have sufficient solar **resource availability** for PV systems to be effective. Most other areas will be suitable for PV from a resource perspective. Wind energy systems require sustained, strong winds to be productive, so unobstructed locations likely have the strongest resources. In general, wind systems will be more appropriate in rural, rather than urban, settings. The biggest factor in biomass power generation system viability is typically having consistent, multi-year access to the biomass resources combusted in the system, whether that is forestry materials like wood waste, agricultural solids, manure for digesters, or other organic materials.

Space requirements are particularly important factors for PV and wind technologies. PV systems require flat areas (roofs, parking canopies, or ground) with sufficient weight-bearing capacity for the solar panels and their racking to be installed and withstand storm-force winds. Therefore, for the most common type of PV application on rooftops, the size and strength of building roofs and PV system components are important considerations, as is the planned useful life of the roofs. The space needed for PV systems is proportional to their capacity, so smaller critical power needs warrant a small system; a 5 kW_{DC} system may only require 500 square feet of solar-suitable roof. Wind energy systems do not remove much land from agricultural use, but they require considerable space between turbines to maximize wind speed and direction through each turbine and to avoid inefficient wake effects on downwind turbines.

Location to nearby utility power lines can help determine whether a renewable energy system, or a microgrid, is on-grid or off-grid. The costs of line extensions to interconnect an on-grid system to a utility meter may be prohibitive if the nearest meter or other point of interconnection (POI) is more than quarter-mile away, or if the land between the renewable energy system and the POI has varied terrain or roadways. Off-grid systems may be the only viable solution in such locations. Additionally, businesses in remote and inland locations typically face longer and more frequent power outages due to their distance from the utility’s coastal generation plants and the condition of transmission networks reaching them. Such locations likely have strong business cases for installing renewable energy systems.

Location decisions should also consider vulnerabilities to natural disasters. For example, wind energy systems should always be constructed to withstand storm-force winds, flooding, and other potential damage from natural disasters that may occur at their sites, or they should be located at alternative sites if adequate protection is not feasible (e.g., away from the coastline if flood risk cannot be mitigated).[34] In selecting PV system components, it is essential to account for protecting against hurricane damage on any part of the island. This includes selection of modules (to withstand bursting from wind pressure and damage from flying debris), fasteners, and racking systems with an extra rail (DOE, 2018b).

The capital and O&M **costs** of renewable electricity systems are another important consideration. As *Exhibit 5* shows, there are significant economies of scale with PV and wind energy systems. If sufficient capital or financing is available and critical power needs are large enough, larger systems will likely be more economically advantageous. For example, the levelized cost of energy for commercial-scale PV systems is about $0.08/kWh lower than for residential-scale systems (Lazard, 2019, p. 3).

The most important long-run cost factor for biomass power generation systems can be the cost of the biomass feedstock; an on-site or adjacent feedstock controlled by the agricultural busines owner (such as manure from confined livestock at dairies) can greatly reduce this cost and make biomass systems economically viable. System costs for all technologies should be evaluated after pursuing all available financial incentives.

The selection of renewable electricity technologies and their configuration should be matched to the type and scale of **critical and non-critical power needs** of the food supply business. If critical power needs are large and round-the-clock, including a source of baseload power (like a biomass system, or pairing solar or wind with a diesel generator in a standalone system or microgrid) is important. In such circumstances, installing solar or wind with battery storage (rather than with a baseload generation source) will likely be cost prohibitive due to the large battery scale needed to assure round-the-clock, reliable power.

If, instead, critical power needs can be intermittently served throughout the day and are not especially large, off-grid PV or wind systems can be a good fit and could avoid the cost of adding battery energy storage.

Critical power needs that are consistent throughout the day, but moderate in scale, can be well-addressed by on-grid PV with battery systems or wind with battery systems. Having grid access provides an added layer of reliability because utility power can be used whenever it is available. Doing so also slows depletion of the batteries, since they will not need to be discharged and re-charged nearly as often as they would in off-grid applications.

As a general principle, biomass power generation systems are a flexible resilient power solution that can be used to meet a variety of critical power needs if the feedstock supply is stable.[35] That is because these systems do not depend on continuous access to solar or wind resources for power, and their power can be cycled up and down like fossil-fuel combustion systems.

Exhibit 6 summarizes attributes and example applications of renewable electricity technology configurations as they relate to critical power needs. Because the focus of this paper is on resilience, only technology configurations that commonly function in islanded mode are included.

[34] For information on protection of wind turbines against hurricane-force winds, see IEC, 2018.
[35] To supplement its traditional biomass feedstocks (like manure from confined livestock in diary operations and wood waste), a U.S. Department of Energy report notes that Puerto Rico "could explore the feasibility of importing biomass pellets from the Southeastern U.S." (DOE, 2018a, p. 28).

EXHIBIT 6: Example Attributes and Applications of Renewable Electricity Technologies

Renewable Electricity Technologies	Utility Connection	Attributes	Example Agricultural Applications
PV or Wind without Battery Storage	**Off-grid**	Intermittent power production; cannot provide round-the-clock power; useful when power needs have very flexible timing	Water pumping, irrigation, pond aeration
PV or Wind with Battery Storage	**Off-grid or On-grid**	Intermittent power production; can address power needs at any time, though battery costs may be prohibitive if critical power needs are large	Cooling at poultry farms, coffee drying, light refrigeration needs, other moderate needs for food packing
PV or Wind combined with Diesel Generator (often with battery storage)	**Off-grid or On-grid**	Consistent power production if there is consistent diesel fuel supply; worse environmental and economic outcomes than renewable-only solutions	Almost any application, including dairy and wholesale/retail refrigeration. Diesel generators are currently serving many back-up power needs in the island's food system.
Biomass Electricity	**Off-grid or On-grid**	Consistent power production if there is consistent feedstock supply	Extensive dairy farm refrigeration, lighting at hydroponic facilities

Conclusions: Implementing Resilient Renewable Electricity

The technical, economic, and environmental justifications for increased deployment of renewable electricity systems for resilience purposes in Puerto Rico's food supply sectors are strong. These systems, as long as they are sited and constructed properly to protect against storm damage, can help food supply businesses decrease the vulnerability of their power supply and save money over time compared to the high price of utility power. From a broader society perspective, there are the additional benefits of reducing the island's dependence on imported fossil fuels and decreasing its GHG emissions.

Firms in Puerto Rico's food supply system have been deploying renewable electricity systems. To date, most have been PV systems. In some cases, they include battery energy storage or other resilience attributes. However, the pace of resilient-focused renewable deployment trails its possibilities largely due to significant upfront capital costs, together with challenges in accessing credit to support these investments (Rivera, 2020). Significantly increasing deployment of renewables will likely require additional support in the form of government policies. There are also actions under current policies that can be taken by individual businesses and collectively by food industry groups across Puerto Rico.[36]

At the ***individual business level***, there are two best practices that can reduce the capital costs of resilient power systems. First, businesses can differentiate between critical and non-critical electricity uses and design systems that prioritize serving only critical uses during grid power

[36] For a summary of food policies related to resilience in Puerto Rico, see Vermont Law School, 2019, pp. 31-33.

outages. Doing so will avoid over-building renewable systems (e.g., including excessively large battery components) and, thereby, reduce costs. Second, implementing energy efficiency (EE) is also recommended before investing in costly on-site power generation and battery storage assets. Given Puerto Rico's high utility power prices, EE investments often have short payback periods and deliver a second benefit of downsizing the amount of critical power that must be served by a renewable energy system during an outage. USDA's NRCS has supported various EE investments in Puerto Rico, including the transition to high-efficiency lighting on poultry farms (Cruz-Arroyo, 2020). Multiple USDA RD programs also support EE and renewable energy investments in Puerto Rico (USDA, 2020b; USDA, 2020c; USDA, 2020d).[37]

At the ***collective action level***, groups of businesses can reduce renewable electricity capital costs through bulk equipment purchases that take advantage of economies of scale. Adjacent businesses may also aggregate their electricity requirements as part of community microgrids. Informal business groupings or formal agricultural trade associations, such as the Puerto Rico Farm Bureau or the Milk Producers Cooperative, can also participate in the utility planning processes associated with the 2019 Puerto Rico Energy Public Policy Act. This Act requires utility electricity to be 100 percent renewable by 2050, highlights customer on-site generation as key to meeting the island's resilience needs, expedites and standardizes utility interconnection reviews for renewable systems under 25 kW and microgrids up to 5 MW in capacity, and supports net metering compensation for excess power from on-site systems (SB 1121, 2019). Such organized participation by consumers in energy proceedings can bolster support for overall policies and improve the chances that food supply resilience concerns are reflected in policy implementation.

[37] A map identifying specific, USDA-supported energy investments in Puerto Rico is available at USDA, 2020e.

Appendix: Interviews Conducted

To supplement the secondary source research and the direct experience of the authors, telephone interviews were conducted with four individuals to inform this paper. These individuals are all located in Puerto Rico, have experience with the island's food supply, forestry, energy, and/or environmental issues, and are listed in *Exhibit 7*. The authors wish to thank these four individuals, as well as experts from the Puerto Rico Farm Bureau and the coffee industry on the island who provided input, for their time and their valuable insights.

EXHIBIT 7: Interviewees in Puerto Rico to Inform Paper

Name	Title	Organization
Luis Cruz-Arroyo	Caribbean Area Director, USDA Natural Resources Conservation Service	U.S. Dept. of Agriculture
William Gould	Director, USDA Caribbean Climate Hub	U.S. Dept. of Agriculture
Guillermo Ortiz-Colón	Assistant Professor	College of Agricultural Sciences, University of Puerto Rico at Mayagüez.
Josué Rivera	State Director, Puerto Rico, USDA Rural Development	U.S. Dept. of Agriculture

References

AWEA. 2020. *U.S. Wind Industry Quarterly Market Report: Fourth Quarter 2019*. American Wind Energy Association. https://www.awea.org/resources/publications-and-reports/market-reports/2019-u-s-wind-industry-market-reports [accessed May 2020].

Caribbean Business. 2019. Puerto Rico Businesses Receive 9 USDA Grants. https://caribbeanbusiness.com/puerto-rico-businesses-receive-9-usda-grants/ [accessed May 2020].

CEG. 2020. *Resilient Power Project Case Study: Cimarron District Forestry Office*. Clean Energy Group. https://www.cleanegroup.org/wp-content/uploads/Cimarron-Case-Study.pdf [accessed May 2020].

Cruz-Arroyo. 2020. ICF Interview with Luis Cruz-Arroyo, Caribbean Area Director, U.S. Department of Agriculture Natural Resources Conservation Service, May 13, 2020.

DOE. 2012. *The U.S. Department of Energy's Microgrid Initiative* as printed in *The Electricity Journal.* U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2016/06/f32/The%20US%20Department%20of%20Energy%27s%20Microgrid%20Initiative.pdf [accessed May 2020].

DOE. 2018a. *Energy Resilience Solutions for the Puerto Rico Grid.* U.S. Department of Energy. https://www.osti.gov/servlets/purl/1463124 [accessed May 2020].

DOE. 2018b. *Solar Photovoltaic Systems in Hurricanes and Other Severe Weather*. U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2018/08/f55/pv_severe_weather.pdf [accessed June 2020].

DOE. 2019. *2018 Distributed Wind Market Report*. U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2019/08/f65/2018%20Distributed%20Wind%20Market%20Report.pdf [accessed May 2020].

DOE. 2020. The Role of Microgrids in Helping to Advance the Nation's Energy System. U.S. Department of Energy. https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/role-microgrids-helping [accessed May 2020].

EIA. 2019. Puerto Rico Electricity Generation Returned to pre-2017 Hurricane Levels One Year Later. U.S. Energy Information Administration, DOE. https://www.eia.gov/todayinenergy/detail.php?id=42095 [accessed May 2020].

EIA. 2020a. Preliminary Monthly Electric Generator Inventory. U.S. Energy Information Administration, DOE. https://www.eia.gov/electricity/data/eia860M/ [accessed May 2020].

EIA. 2020b. Puerto Rico Territory Energy Profile. U.S. Energy Information Administration, DOE. https://www.eia.gov/state/print.php?sid=RQ [accessed May 2020].

EIA. 2020c. What is U.S. Electricity Generation by Energy Source? U.S. Energy Information Administration, DOE. https://www.eia.gov/tools/faqs/faq.php?id=427&t=3 [accessed June 2020].

EIA. 2020d. Electric Power Monthly: Estimated Net Summer Solar Photovoltaic Capacity from Utility and Small Scale Facilities (data for February 2020). U.S. Energy Information Administration, DOE. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_01_a [accessed May 2020].

EPA. 2018. *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*. U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf [accessed June 2020].

EPA. 2019. *Interconnection: Plugging RE-Powering Sites into the Electric Grid*. U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2019-10/documents/interconnection_plugging_re_powering_sites_into_the_electric_grid_oct2019_508.pdf [accessed May 2020].

EPRI. 2018. *Energy Storage Technology and Cost Assessment: Executive Summary*. Electric Power Research Institute. https://www.epri.com/#/pages/product/000000003002013958/?lang=en-US&lang=en-US&lang=en-US&lang=en-US [accessed May 2020].

FAO. 2018. Growing an Agricultural Revolution in Puerto Rico. Food and Agriculture Organization of the United Nations. http://www.fao.org/in-action/agronoticias/detail/en/c/1095391/ [accessed June 2020].

Gallucci, Maria. 2018. Rebuilding Puerto Rico's Power Grid: The Inside Story. IEEE Spectrum. https://spectrum.ieee.org/energy/policy/rebuilding-puerto-ricos-power-grid-the-inside-story [accessed May 2020].

Government of Puerto Rico, et al. n.d. *The Grid Modernization of Puerto Rico*. Government of Puerto Rico, Puerto Rico Electric Power Authority, and Central Office for Recovery, Reconstruction, and Resiliency. https://recovery.pr/documents/Grid%20Modernization%20for%20Puerto%20Rico-English1.pdf [accessed May 2020].

GTM Research. 2019. Levelized Cost of Energy for Lithium-Ion Batteries is Plummeting. https://www.greentechmedia.com/articles/read/report-levelized-cost-of-energy-for-lithium-ion-batteries-bnef [accessed May 2020].

IEC. 2018. How Well Can Wind Turbines Cope with Hurricanes? International Electrotechnical Commission. https://blog.iec.ch/2018/09/how-well-can-wind-turbines-cope-with-hurricanes/ [accessed June 2020].

INL. 2016. *Cyber Threat and Vulnerability Analysis of the U.S. Electric Sector*. Idaho National Laboratory. https://www.energy.gov/sites/prod/files/2017/01/f34/Cyber%20Threat%20and%20Vulnerability%20Analysis%20of%20the%20U.S.%20Electric%20Sector.pdf [accessed May 2020].

IRENA. 2012. *Renewable Energy Technologies: Cost Analysis Series: Biomass for Power Generation.* International Renewable Energy Agency. https://www.irena.org/publications/2012/Jun/Renewable-Energy-Cost-Analysis---Biomass-for-Power-Generation [accessed May 2020].

Juwi. 2014. Poppy and Solar Farm. Juwi Renewable Energies Limited. https://www.flickr.com/photos/126337375@N05/15756820490/ [accessed June 2020].

Lazard. 2017. *Lazard's Levelized Cost of Energy Analysis – Version 11.0.* https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf [accessed May 2020].

Lazard. 2019. *Lazard's Levelized Cost of Energy Analysis—Version 13.0.* https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf [accessed June 2020].

LBNL. 2019. *Tracking the Sun: Pricing and Design Trends for Distributed Photovoltaic Systems in the United States - 2019 Edition.* Ernest Orlando Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/default/files/tracking_the_sun_2019_report.pdf [accessed May 2020].

Mueller, et al. 2010. New Seismic Hazard Maps for Puerto Rico and the U.S. Virgin Islands. Charles Mueller, Arthur Frankel, Mark Petersen, and Edgar Leyendecker, *Earthquake Spectra*, Volume 26, No. 1 (February 2010). https://journals.sagepub.com/doi/10.1193/1.3277667 [accessed May 2020].

NAB. 2019. *Resolution 19-23*. Northwest Arctic Borough Assembly. http://www.nwabor.org/wp-content/uploads/Signed-Res-19-23-High-Energy-funds.pdf [accessed June 2020].

NCCETC. 2020. (Federal) Programs. NC Clean Energy Technology Center. https://programs.dsireusa.org/system/program?state=US [accessed May 2020].

NIBS. 2016. *Whole Building Design Guide, Biomass for Electricity Generation*. National Institute of Building Sciences. https://www.wbdg.org/resources/biomass-electricity-generation [accessed May 2020].

NREL. 2015. *Energy Snapshot: Puerto Rico*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy15osti/62708.pdf [accessed May 2020].

NREL. 2016. *Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/67337.pdf [accessed May 2020].

NREL. 2018. *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72399.pdf [accessed May 2020].

NREL. 2019. Beneath Solar Panels, the Seeds of Opportunity Sprout. National Renewable Energy Laboratory. https://www.nrel.gov/news/features/2019/beneath-solar-panels-the-seeds-of-opportunity-sprout.html [accessed June 2020].

Ortiz-Colón, Guillermo. 2018. *Food Systems, Development, and Sustainability: The Case Study of the Dairy Industry of Puerto Rico*. College of Agricultural Sciences, University of Puerto Rico at Mayagüez.

Pagani, et al. 2018. *OpenQuake Global Seismic Hazard Map*. M. Pagani, J. Garcia-Pelaez, R. Gee, K. Johnson, V. Poggi, R. Styron, G. Weatherill, M. Simionato, D. Viganò, L. Danciu, D. Monelli. https://maps.openquake.org/map/global-seismic-hazard-map/#3/4.13/-114.26 [accessed May 2020].

Port Authority. 2017. *Port Authority of NY & NJ Support to Puerto Rico*. Port Authority of New York & New Jersey. https://corpinfo.panynj.gov/files/uploads/documents/board-meeting-information/board-committee-meeting-presentations/10-26-17-Board_-_PA_Support_to_Puerto_Rico_-_Hurricane_Maria.pdf [accessed May 2020].

Powering Agriculture. n.d. Smart Grid on Main Street: Electricity and Value-added Processing for Agricultural Goods. https://poweringag.org/innovators/smart-grid-main-street-electricity-value-added-processing-agricultural-goods [accessed June 2020].

PR DOH. 2019. *Puerto Rico Disaster Recovery Action Plan*. Puerto Rico Department of Housing. https://www.cdbg-dr.pr.gov/wp-content/uploads/2019/10/111618_PRDOH-Action-Plan_Substantial-Amendment.pdf [accessed June 2020].

PREB. 2018. *Regulation on Microgrid Development*. Puerto Rico Energy Bureau. http://www.pridco.com/real-estate/Pages/RFP_FY2018-2019-002_Anasco/Regulation_9028-Regulation_on_Microgrid_Development.pdf [accessed June 2020].

PREPA. 2017. *Puerto Rico Electric Power Authority Fiscal Plan*. Puerto Rico Electric Power Authority. http://www.aafaf.pr.gov/assets/fiscal-plan---pr-electric-power-authority.pdf [accessed May 2020].

PREPA. 2019. *2019 Fiscal Plan for the Puerto Rico Electric Power Authority*. Puerto Rico Electric Power Authority. https://aeepr.com/es-pr/Documents/Exhibit%201%20-%202019%20Fiscal_Plan_for_PREPA_Certified_FOMB%20on_June_27_2019.pdf [accessed May 2020].

Rivera. 2020. ICF Interview with Josué Rivera, State Director, Puerto Rico, U.S. Department of Agriculture Rural Development, May 13, 2020.

RMI. 2019. 10 Puerto Rican Schools Receive Resilient Microgrids. Rocky Mountain Institute. https://rmi.org/press-release/10-puerto-rican-schools-receive-resilient-microgrids/ [accessed June 2020].

RPRAC. 2018. *ReImagina Puerto Rico: Energy Sector Report*. Resilient Puerto Rico Advisory Commission. https://reimaginapuertorico.org/resources/ [accessed May 2020].

SB 1121. 2019. *Puerto Rico Energy Public Policy Act*. Puerto Rico Senate Bill 1121. https://aeepr.com/es-pr/QuienesSomos/Ley17/A-17-2019%20PS%201121%20Politica%20Publica%20Energetica.pdf [accessed May 2020].

Schneider Electric. 2015. 5 Places Where Critical Power Plays a Crucial Role. https://blog.se.com/power-management-metering-monitoring-power-quality/2015/06/18/5-places-where-critical-power-plays-a-crucial-role/ [accessed May 2020].

Siemens. 2019. *Puerto Rico Integrated Resource Plan 2018-2019*. Siemens Industry, Inc. https://aeepr.com/es-pr/QuienesSomos/Ley57/Plan%20Integrado%20de%20Recursos/IRP2019%20-%20Ex%201.00%20-%20Main%20Report%20%20REV2%2006072019.pdf [accessed May 2020].

USAID. 2018. Bamiyan Renewable Energy Program. U.S. Agency for International Development. https://www.usaid.gov/energy/mini-grids/case-studies/afghanistan-hydropower/ [accessed June 2020].

USDA. 2011. *Solar Energy Use in U.S. Agriculture: Overview and Policy Issues*. U.S. Department of Agriculture. https://www.usda.gov/oce/reports/energy/Web_SolarEnergy_combined.pdf [accessed April 2020].

USDA. 2015. Puerto Rico's Secretary of Agriculture visits NIFA, Addresses Food Security Issues. U.S. Department of Agriculture. https://nifa.usda.gov/announcement/puerto-rico%E2%80%99s-secretary-agriculture-visits-nifa-addresses-food-security-issues [accessed June 2020].

USDA. 2018. Caribbean Area Agriculture, Watershed Recovery One Year Post María. U.S. Department of Agriculture. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/pr/newsroom/features/?cid=nrcseprd1420889 [accessed May 2020].

USDA. 2019a. *High Energy Cost Grants, 2019 High Energy Cost Grant Awardees*. U.S. Department of Agriculture. https://www.rd.usda.gov/programs-services/high-energy-cost-grants [accessed June 2020].

USDA. 2019b. *USDA Rural Development, Rural Energy for America Program* (grant list, August 19, 2019). U.S. Department of Agriculture. https://www.rd.usda.gov/files/REAP_NR_CHART_under200000k81919.pdf [accessed May 2020].

USDA. 2019c. *2017 Census of Agriculture: United States Summary and State Data*, Volume 1, Geographic Area Series, Part 51. U.S. Department of Agriculture. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf [accessed April 2020].

USDA. 2020a. *Puerto Rico (2018) Island and Regional Data, Census of Agriculture*. U.S. Department of Agriculture. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Outlying_Areas/Puerto_Rico/prv1.pdf [accessed June 2020].

USDA. 2020b. USDA Rural Development: Programs & Services. U.S. Department of Agriculture. https://www.rd.usda.gov/programs-services [accessed June 2020].

USDA. 2020c. Rural Energy for America Program: Renewable Energy Systems & Energy Efficiency Improvement Guaranteed Loans & Grants. U.S. Department of Agriculture. https://www.rd.usda.gov/programs-services/rural-energy-america-program-renewable-energy-systems-energy-efficiency [accessed June 2020].

USDA. 2020d. Rural Energy for America Program: Energy Audit & Renewable Energy Development Assistance Grants. U.S. Department of Agriculture. https://www.rd.usda.gov/programs-services/rural-energy-america-program-energy-audit-renewable-energy-development-assistance [accessed June 2020].

USDA. 2020e. Energy Investment Map. U.S. Department of Agriculture. https://www.usda.gov/energy/maps/maps/Investment.htm [accessed June 2020].

U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* https://science2017.globalchange.gov/ [accessed May 2020].

Vermont Law School. 2019. *Food Systems Resilience: Concepts & Policy Approaches*. Center for Agriculture and Food Systems at Vermont Law School, with support from USDA National Agricultural Library.

https://www.nal.usda.gov/sites/www.nal.usda.gov/files/food_systems_resilience_concepts_policy_approaches_final.pdf [accessed June 2020].