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Puerto Rico's Electric Power System: An Analysis of Contemporary Failures and the Opportunity to Rebuild a More Resilient Grid, including the Development of a Utility-Scale Solar Farm on the Island Municipality of Culebra

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ABSTRACT

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Puerto Rico's grid was decimated in 2017 after experiencing back-to-back hurricanes – Maria and Irma. Although the hurricanes caused tremendous damage and hardship to the island, it also created the right circumstances for the local energy landscape to transition toward a more resilient and sustainable model. Through an analysis of recent challenges by the local electric utility PREPA, and subsequent fallout from the hurricanes, we see that they now hold a unique opportunity to redeem themselves by taking advantage of catalyzed resources to rebuild a better system. One region that could greatly benefit from an improved and reimagined grid are the two island municipalities of Culebra and Vieques. After investigating PREPA's failures over the last 10 years, and responses to them, we breakdown the possibility of building a utility-scale solar farm on Culebra and how it may contribute to the island's energy independence. Finally, we look at the potential impacts that a project of this magnitude could have on the Caribbean and the way we think about small islands and their power systems.

Professor David I. Bell, Ed.D. Chief Instructor

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EXECUTIVE SUMMARY

When it comes to Development, island nations have historically faced a unique set of challenges. So much so, that the United Nations has created a specific category through which to analyze and support them, identifying these nations through the lens of what they refer to as *Small Island Developing States (SIDS)*[1]. Most of the constraints encountered by these islands relate to their remote existence and very limited natural resources, emphasized by the fact that they are surrounded entirely by water.

Their isolated nature makes it extremely difficult to adequately prepare for and respond to natural disasters, in the sense that we are traditionally used to seeing with bordering communities and the use of mutual assistance. The challenge of responding to natural disasters is compounded by the emerging threat of climate change and the way it has contributed to volatile and intensified weather events in the geographic areas where these small islands are typically located – the Caribbean, Pacific Islands, and the Indian Ocean/South China Sea[2]. A major byproduct of these weather events, and substantial disruptor, to small islands has been the damage sustained to electric power systems, or *the grid*.

An island that has been particularly affected by damage to their grid during recent natural disasters has been Puerto Rico – an archipelago in the Caribbean Sea primarily made up of one mainland island and two smaller island municipalities to the east. Although Puerto Rico has experienced many catastrophic weather events over the last 100 years, none have been as severe or destabilizing as Hurricane Maria[3], which tore through the island in September of 2017 and destroyed the island's electrical infrastructure. Ironically, it is precisely due to the devastation of their power system at the hands of Hurricane Maria that they now face a unique opportunity to rebuild it, based around the concept of a *decentralized grid* with more innovative and flexible technologies[4], and this is especially true for one of Puerto Rico's two island municipalities – *Culebra* (with Vieques being the other). These island municipalities are better poised than ever

[1] "Small Island Developing States - Small Islands Big(Ger) Stakes." *United Nations – OHRLLS*, 2011
[2] "Small Island Developing States - Small Islands Big(Ger) Stakes." *United Nations – OHRLLS*, 2011, pp. 4-5
[3] "Hurricanes and Tropical Storms in Puerto Rico from 1900 to 1979, 1980 to 2005." *The Puerto Rico Hurricane Center*
[4] Puerto Rico Energy Resiliency Working Group. *"Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico."* Dec. 2017, pp. 6-7

before to increase their resiliency to natural disasters by reimagining and rebuilding their electric power system to potentially become energy independent or operate in a micro/minigrid[5] state.

In order to properly legitimize the need for a transition towards decentralizing the electric power system of Culebra (and Puerto Rico in general), we must first understand the historical context of this undertaking and how previous failures to follow through on promised improvements have led to major grief while subsequently increasing the support for sustainable energy infrastructure projects by the local and international communities. A project of this scope and magnitude would not only be beneficial, but in fact may be crucial, to the long-term sustainable development of the two island municipalities.

Through the inclusion of three separate but related Parts, this paper will first describe the *challenges* and *responses* to operating an electric power grid in Puerto Rico under increasingly hostile weather events and what the impacts have been to the island municipalities, then provide a preliminary *project design* and *analysis* for a utility-scale[6] solar farm on Culebra, with a final assessment of *future considerations* and possible *implications* that such a project may have throughout the region.

[5] "Resilient by Design: Enhanced Reliability and Resiliency for Puerto Rico's Electric Grid." *Siemens*, 2018, p. 1 – minigrids differ from microgrids in the sense that they supply larger areas than traditional microgrids.
[6] "Renewable Energy: Utility-Scale Policies and Programs." *U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy* – utility-scale defined as larger than or equal to 10MW.

PART I

Puerto Rico's Electric Power System Challenges and Responses

Small Islands

Through the framework of Small Island Developing States, we understand that many islands face similar difficulties on their quests to develop; whether it be infrastructure, economic, social, or human development, these islands are confronted with major challenges compared to countries that share land borders. Island nations must deal with the increased cost of transportation of goods since the means of either importing or exporting is through marine vessel or aviation travel, which happen to be two of the most expensive means of transportation; freight by train, road, pipeline are significantly less expensive[7]. These costs are frequently passed on to consumers making the average cost of living much higher than other types of geographic areas[8].

High transportation costs of importing resources to the islands have been responsible for increased prices in fuel, food, medicine, building materials, clothes, water, and electricity[9]. Increased costs to export goods have had similar undesirable effects such as limiting economic growth potential by restricting the ability to compete in the global marketplace; export led growth has generally had low ceilings for island nations[10]. Puerto Rico has struggled tremendously with the issue of transportation in part due to its relationship with the United States (U.S.) and its legal requirement to follow the Merchant Marine Act of 1920, also referred to as the Jones Act, which mandates shipment of goods between American harbors be transported by U.S. made and owned vessels. Studies show that this method of using U.S. flagged sea transport is on average 2.7 times more expensive than other foreign based sea transport costs[11]. We see similar impacts of this legislation in other territories not part of the continental U.S. – Hawaii, Alaska, and Guam.

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[7] "Transportation Economic Trends: Cost of Transportation, Costs Faced by Producers." *U.S. Department of Transportation, Bureau of Transportation Statistics*

[8] "Access to Macroeconomic & Financial Data: Consumer Price Index, All Countries: Transport." *International Monetary Fund*

[9] "Small Island Developing States - Small Islands Big(Ger) Stakes." *United Nations – OHRLLS*, 2011, pp. 14-5

[10] Kemp-Benedict, E., Drakes, C. and Laing, T.J. "Export-Led Growth, Global Integration, and the External Balance of Small Island Developing States." *Stockholm Environment Institute U.S. Economies*, 2018, pp. 13-4

[11] "Comparison of U.S. and Foreign-Flag Operating Costs." *U.S. Department of Transportation: Maritime Administration*, 2011, pp. 4-5

The high costs of transportation and limited economic growth, have made it difficult for Puerto Rico to adequately prepare for and react to natural disasters. Small islands are faced with preparing for and dealing with major weather events in very limited capacities due to their strained economic resources and isolated geography. This makes climate change an ever-increasing existential threat that needs to be addressed; we are finding out in the 21st century that islands are ill-equipped to properly handle events like hurricanes, droughts, earthquakes, and receding coastlines.

Climate Change

The Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5) shows with high confidence that weather events like tropical cyclones and sea level rise have devastating impacts on small island communities in the present day, and will have progressively negative impacts in the future, with both high and current levels of adaptation[12]. One of the main 'key risks' presented in this report focuses on island infrastructure, including electric power systems and the probability that it will suffer losses due to these climatic drivers, as seen in the top left corner of Figure 1.1[13].

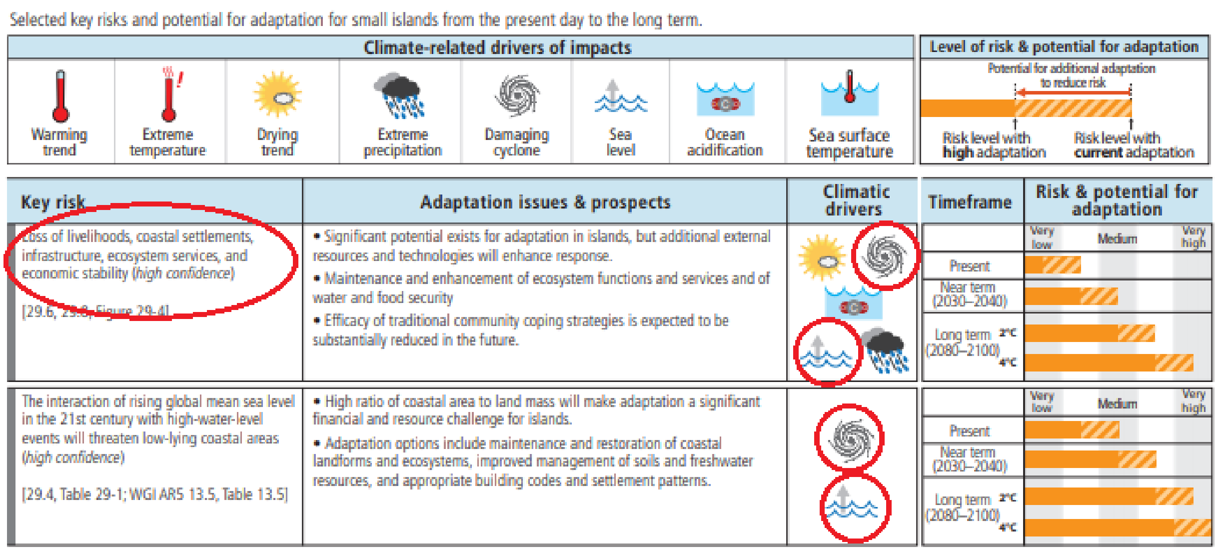

Figure 1.1 – IPCC AR5 Projected Climate Change Impacts to Small Islands

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[12] "Chapter 29: Small Islands." *Intergovernmental Panel on Climate Change 5th Assessment Report (AR5): Impacts, Adaptation, and Vulnerability - Part B Regional Aspects*, 2014, pp. 1634-637

[13] "Chapter 29: Small Islands." *Intergovernmental Panel on Climate Change 5th Assessment Report (AR5): Impacts, Adaptation, and Vulnerability - Part B Regional Aspects*, 2014, p. 1635

Some of the world's most powerful and recognized organizations, relying on mounting scientific data, are predicting that the trajectory of climate change will continue trending upwards and that we are likely to experience intensified storm activity and greater weather extremes caused by a warming planet[14]. In fact, Puerto Rico is listed as the *number one* country most affected by extreme weather events, both in terms of fatalities and economic losses (PPP), during the years 1999 – 2018, according to the Climate Risk Index 2020[15]. This is primarily due to the effects of exceptional catastrophes, and this is what was experienced with Hurricane Maria. The hurricane season of 2017 was unprecedentedly destructive for Puerto Rico, which experienced back-to-back Category 5 hurricanes for the first time in its history, during the month of September 2017 – *Hurricanes Irma and Maria*, respectively.

Hurricane Irma passed by Puerto Rico, 60 miles north of the island, as a Category 5 hurricane during the evening of September 6, 2017. Though the hurricane did not pass directly over the territory, the storm caused significant island-wide damage, especially along the northern coast, Puerto Rico's most densely populated region, as well as the two island municipalities. The highest recorded sustained wind gusts were in Culebra, topping 110 mph, leading to widespread outages in power, telecommunications, and water infrastructure (both supply and wastewater treatment)[16]. These island municipalities were declared disaster zones by then-governor Ricardo Rossello. Similar impacts were felt along the mainland of Puerto Rico, experiencing major storm surge and flooding in the capital district, the uprooting of trees, collapsing of bridges, failing of levees, destruction of homes, and outages in power, communications, and water for more than a million residents on the island[17]. Three deaths were attributed to the storm and restoration efforts lasted weeks. As they were nearing the completion of power and telecommunications restoration,

[14] a) Knutson, Thomas, et al. "Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution." *Bulletin of the American Meteorological Society*, October 2019
b) "Taking the Heat - Making Cities Resilient to Climate Change." *Goldman Sachs: Global Markets Institute*, September 2019
c) "4° Turn Down the Heat: Why a 4°C Warmer World Must Be Avoided." *World Bank: Potsdam Institute for Climate Impact Research and Climate Analytics*, November 2012

[15] Eckstein, David, et al. "Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2018 and 1999 to 2018." *GermanWatch: Global Climate Risk Index 2020*, December 2019, pp. 9-10

[16] Cangialosi, John P., et al. "National Hurricane Center Tropical Cyclone Report: Hurricane Irma 30 August - 12 September 2017." *National Oceanic and Atmospheric Administration and National Weather Service*, June 2018, pp. 15-29

[17] Alvarado, Cindy B. "Wrap-up of Damages in P.R. Caused by Hurricane Irma." *Caribbean Business*, 17 September 2017

the island was struck with a direct impact from Category 5 Hurricane Maria just two weeks later on September 20, 2017. Hurricane Irma brought into question the integrity of Puerto Rico's grid, but Hurricane Maria completely exposed it for the weak and frail system that it was.

<u>Puerto Rico Electric Power Authority</u>

The Puerto Rico Electric Power Authority (PREPA) manages and operates the island's grid, made up of approximately 40 generating stations, 2,500 miles of transmission lines (>38kV), 30,000 miles of distribution lines (<38kV), 340 substations, and two 38kV submarine cables that connect Culebra and Vieques to the mainland power system[18]. See Figure 1.2 below for a high-level overview of these assets.

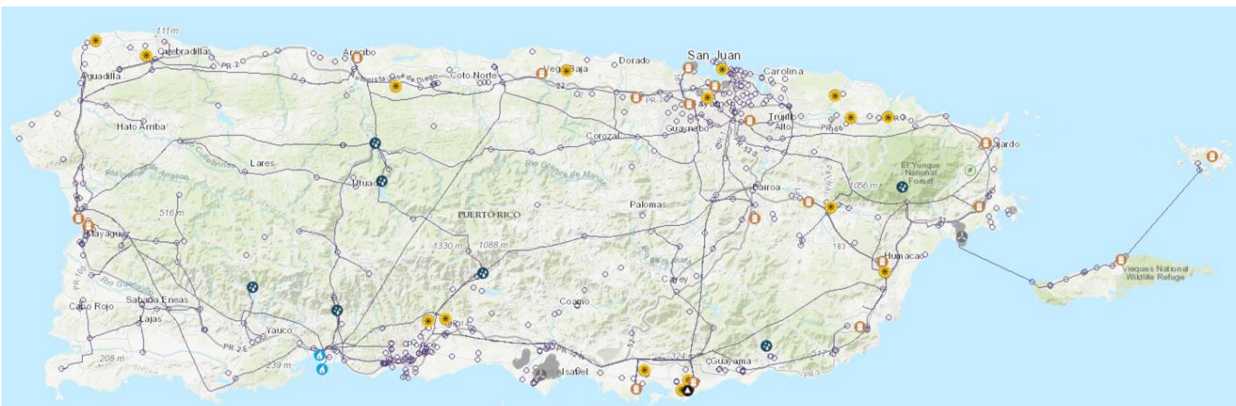

Figure 1.2 – U.S. Energy Information Administration GIS Map of Puerto Rico Electric Power System

This network serves over 1.5 million residential, commercial, and industrial customers on the island, making it the largest publicly owned electric utility in the U.S.[19], and one of the most expensive with typical rates being 30% higher than average U.S. prices for electricity on a per kilowatt hour (kWh) basis[20]. The only states whose electricity rates are comparable are Hawaii and Alaska. At first glance, PREPA's resources may appear to represent a robust system, but upon examination one can see this is not the case.

Out of the 40 generating stations, only 8 locations serve as baseload providers, supplying 90% of the island's power demand – AES, Aguirre, Cambalache, Costa Sur, EcoElectrica,

[18] "Puerto Rico Territory Profile Overview." *U.S. Energy Information Administration*, 2020
[19] "Infrastructure Interdependency Assessment: Puerto Rico." *Department of Homeland Security*, May 2018, p. 43
[20] "Puerto Rico Territory Profile Overview." *U.S. Energy Information Administration*, 2020

Mayaguez, Palo Seco, and San Juan power plants[21]. All of these are fossil fuel power plants and require the importation of either oil, coal, or liquefied natural gas (LNG) to produce electricity. Most of the fuel imports are delivered through the harbors at either San Juan in the north or Ponce in the south, with special offshore terminals in Peñuelas for the delivery of LNG[22]. The transmission and distribution (T&D) infrastructure topology reflects a system that wraps around the island's perimeter, heavily concentrating itself on the coastline to produce a giant loop, or ring. Only 6 high voltage, long distance transmission lines (2 – 230kV, 4 – 115kV) run through the *interior* of the island, connecting the north and south grids, as seen in Figure 1.3.

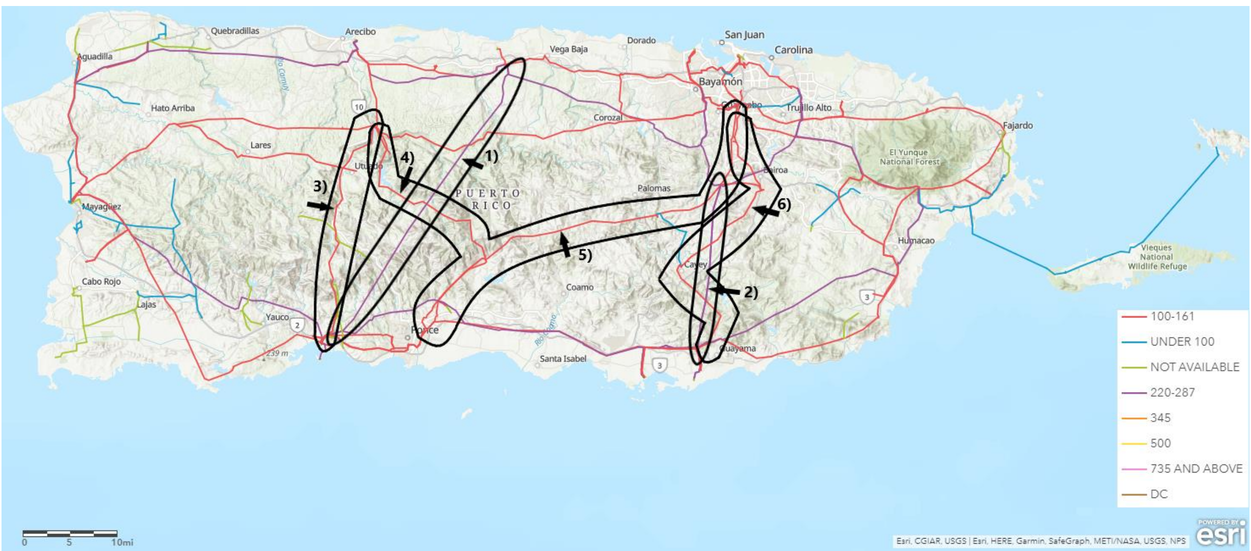

Figure 1.3 – Homeland Infrastructure Foundation-Level Data GIS Map Highlighting Puerto Rico Interior Transmission Lines

Transmission lines are the backbone of centralized grids and are crucial to electric power systems by transporting large amounts of power far distances from where it is produced to where it is consumed. They typically supply power to several substations along its path which then branch off at distribution voltages to feed the utility customers' electrical demand. PREPA's high voltage transmission lines that run through the interior of the country are important components of the

[21] a) "40th Annual Report on the Electric Property of PREPA." *Puerto Rico Electric Power Authority*, June 2013, pp. 8-27
b) "2019 Fiscal Plan for PREPA." *Puerto Rico Electric Power Authority*, June 2019, pp. 35-6
[22] "Infrastructure Interdependency Assessment: Puerto Rico." *Department of Homeland Security*, May 2018, p. 32

overall network that help transport electricity from the south where most is produced, to the north where most is consumed[23].

These two primary characteristics form the foundation of the overall structure to the Puerto Rico electric power system – few centralized generating stations (favoring the south), with few high voltage transmission lines, and substations concentrated along the coasts. The grouping of power plants in small pockets and conductors concentrated around the periphery increase the risk of blackout and form considerable vulnerabilities for single points of failure. If any one element is lost, it may produce overloads on the remaining elements and place stress on the system. If a generating station is lost, or a major transmission line fails, the grid's reliability could become jeopardized and possibly run the risk of shutting itself down to protect the rest of its components from damage[24]. Not to mention the risk of only having two ports available for the importation of fuel; if one port is lost, significant disruptions to the supply chain could occur, as well as complete loss of natural gas if the LNG terminal is taken out of service[25].

Additionally, much of the infrastructure was not built to withstand strong weather events and high wind conditions – only 15% of transmission elements were built to endure a Category 4 hurricane, with the rest built for lesser standards[26]. When assessed in its totality and all components are taken into consideration, one can see that the electric power system in Puerto Rico was inadequately designed and woefully underprepared to survive the impacts of major weather events. This was made quite clear and observed through the catastrophic damage experienced during the hurricane season of 2017, and in particular with Hurricane Maria. The island and its utility company, already fatigued from the fallout and restoration of Hurricane Irma, had no choice but to brace itself for yet another Category 5 Hurricane, this one anticipated to be much worse.

[23] "Puerto Rico Public-Private Partnership for the Electric Power Transmission and Distribution System." *Puerto Rico Public-Private Partnership Committee Report*, May 2020, pp. 16 and 235
[24] Campbell, Richard J., et al. "Repair or Rebuild: Options for Electric Power in Puerto Rico." *Congressional Research Service*, 16 November 2017, pp. 3-7
[25] "Infrastructure Interdependency Assessment: Puerto Rico." *Department of Homeland Security*, May 2018, pp. 48-50
[26] "Grid Modernization Plan for Puerto Rico." *Navigant Consulting Group prepared for Puerto Rico Central Office of Recovery, Reconstruction and Resiliency*, December 2019, pp. 22-3

Hurricane Maria

Hurricane Maria absolutely decimated PREPA's electrical network and plunged the *entire* island into darkness – destroying thousands of poles and conductors, rendering 74% of substations inoperable, flooding the main generation plants and the utilities' two control centers, and disconnecting the submarine cable that powers the two island municipalities (highlighted below in Figure 1.4)[27].

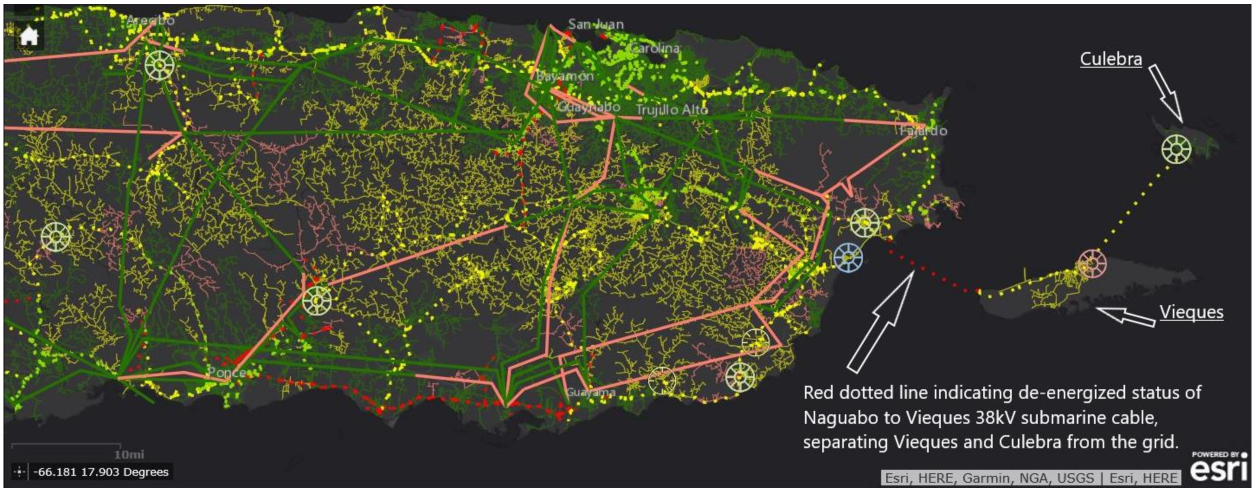

Figure 1.4 – U.S. Army Corps of Engineers GIS Map Pointing to De-Energized Submarine Cable to Vieques

Strom damage assessments concluded that there were 1,694 broken wood poles, 551 broken concrete poles, 111 broken steel poles, and more than 600 damaged transmission towers. Out of the 334 substations, only 12 were deemed to be in good condition, with 121 suffering minor damage and 131 experiencing major damage, including flooding, damaged switches and transformers, and broken instrumentation and communications equipment[28]. More than 900 transmission lines were found to have sustained failures in either the conductors themselves or the insulators that connect them to the lattice towers[29]. Almost every single type of electrical device that makes up the grid was impacted by the storm – *generators*, *substations*, *conductors*, *switches*, *communications equipment*, *insulators*, *poles/towers*, *control centers*, *protective relays*, and the list goes on. The generating stations were able to be brought back online relatively quickly after

[27] "Request for Federal Assistance for Disaster Recovery: Build Back Better." *Government of Puerto Rico*, November 2017, pp. 17-21

[28] Puerto Rico Energy Resiliency Working Group. "Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico." Dec. 2017, pp. 18-27

[29] "Grid Modernization Plan for Puerto Rico." *Navigant Consulting Group prepared for Puerto Rico Central Office of Recovery, Reconstruction and Resiliency*, December 2019, p. 23

the storm (most within a matter of weeks[30]), but the extensive damage to the T&D network meant there was no way to transport the power to where it was needed. The damages to the submarine cables powering the island municipalities were so extensive it took more than a year and a half to finally place the section between Vieques and Culebra back into service, requiring the islands to use emergency diesel generators to supply their power needs[31]. Repairing and rebuilding this infrastructure was a herculean task and required the cooperation and resources of several organizations, including the federal government, over an extended period of time.

It took the utility, under the leadership of the U.S. Army Corps of Engineers (USACE) and Federal Emergency Management Agency (FEMA), 11 months to restore power to 100% of its customers, making it the longest power outage ever in U.S. history[32]. This historic power outage left an indelible mark on the island and was responsible for the breakdown of critical facilities and services all over the island[33]. To appreciate the impact of a prolonged island-wide blackout, we must understand the relationship that power has with other sectors and its significance in the operational continuation of the services they provide, for example – emergency response, water supply, healthcare, education, and telecommunications. The tremendous ancillary consequences of this blackout were devastating and felt throughout the island. The negative impacts of Hurricane Maria were certainly felt in other areas of society caused primarily by the physical damage sustained to buildings, roads, bridges, agricultural crops, ports, and airports, but the damage sustained to *electrical infrastructure* had especially far-reaching implications.

Hospitals were unable to power their buildings and medical equipment, water supply and treatment facilities were unable to provide or treat water, the telecommunications towers went offline with subsequent loss of wireless connectivity, emergency responders were unable to connect directly with the public[34]. All this occurred within a matter of days after Hurricane Maria struck the island and people were still very much in survival mode. Hundreds of thousands of structures were damaged, people's homes had been destroyed and families left to the elements,

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[30] Gallucci, Maria. "Rebuilding Puerto Rico's Power Grid: The Inside Story." *Institute of Electrical and Electronics Engineers: Spectrum Journal*, 12 March 2018

[31] Vélez, Eva L. "Electric Power Transmission to Culebra, Puerto Rico Restored." Caribbean Business, 20 March 2019

[32] "Puerto Rico Territory Profile Overview." *U.S. Energy Information Administration*, 2020

[33] "Infrastructure Interdependency Assessment: Puerto Rico." *Department of Homeland Security*, May 2018, pp. 35-70

[34] "Request for Federal Assistance for Disaster Recovery: Build Back Better." *Government of Puerto Rico*, November 2017

supermarkets had lost millions of refrigerated inventory, all commercial and industrial activity was halted, hotels and emergency shelters went without power, banks were offline with no way of distributing funds, there was no way for people who were trapped to contact emergency personnel, disaster rescue and recovery efforts were limited during nighttime due to the lack of streetlighting. 90% of the island's water system was lost due to damages to the grid which powered the system's pumps and control equipment [35]. All 185 hospitals and health clinics suffered serious structural damage and power loss; one hospital on the island of Vieques was completely destroyed[36]. Figure 1.5 shows the relationship electricity shares with other sectors and its foundational impact.

The island municipalities of Vieques and Culebra were left without *power* and *communications* for weeks before ferry transport was restored, and utility personnel were able to make their way out to connect large diesel generators with the help of USACE[37]. These generators were used intermittently, primarily during the evening hours to help power lighting, cooling, and telecoms infrastructure. It would take over a year before these islands were finally reconnected to the grid through submarine cable. Over the span of several months, once responses and recovery efforts had ramped up, the USACE had installed a total of 879 commercial sized generators that could power hospitals, schools, emergency management centers, transportation hubs, water facilities, communications towers, and even small islands as was the case for Vieques and Culebra[38]. Electrical power was *vital* for recovery operations and life in general – as you can see its impact on the island was enormous.

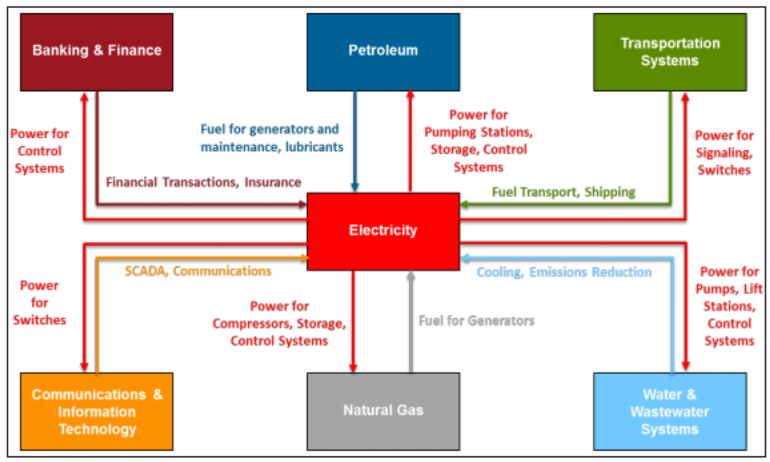

Figure 1.5 – Department of Energy Infographic Displaying Interdependency of Electricity with Other Sectors

[35] "Request for Federal Assistance for Disaster Recovery: Build Back Better." *Government of Puerto Rico*, November 2017, pp. 70-9

[36] "Request for Federal Assistance for Disaster Recovery: Build Back Better." *Government of Puerto Rico*, November 2017, pp. 24-9

[37] Arnold, Elizabeth. "Vieques No Longer Living on Generators, but Still in Need of Energy Independence." University of Minnesota: Resilience Through Innovation in Sustainable Energy, 15 January 2019

[38] Bourgeois, Reginald. "The Maria Chronicles: The District Deploys." *U.S. Army Corps of Engineers*, 4 October 2018

Two weeks after the storm hit, then-governor Ricardo Rossello stated there were 16 confirmed deaths as a result of Hurricane Maria, later increased to 64 as the official number for storm related fatalities by the local government[39]. Although the immediate aftermath of the storm led to a modest death count, that number would quickly balloon to the thousands as a result of investigative research conducted by George Washington University. Six months after the storm passed, the school published a study that attributed *2,975* deaths to Hurricane Maria and its impact on the island[40]. The study reported that these deaths were mostly incurred by vulnerable members of the public who had limited financial resources and had experienced chronic or specialized medical conditions and were unable to secure the services they needed, from organizations and emergency personnel lacking a variety of resources, including *electrical power*.

The destruction to local infrastructure and destabilization of society, caused in part due to the loss of the electric power system, led to a massive exodus of people and businesses from Puerto Rico. Studies have indicated that more than 200,000 people have migrated from the island in search of better living conditions, including access to reliable power[41]. The electrification of society is causing the grid to have a much greater influence over the public, as power was once seen as a luxury, it has quickly moved toward necessity and has become an important facet of everyday life. Electricity is one of the cornerstones to development and increasingly relied upon throughout the world to meet the needs of its people, even comprising one of the United Nations' Sustainable Development Goals – #7 Ensuring access to reliable energy for all[42].

As the reliance on electric power increases throughout the world, the impacts of the *loss* of that power also increase. We see with Puerto Rico that the consequences and ancillary effects of losing the grid were overwhelming and devastating. Although this blackout was caused by a hurricane, many experts question the underlying factors that contributed to the near total failure and lengthy rebuild of what was supposed to be a modern and reliable system. We now know the grid in Puerto Rico was inadequately designed and managed, particularly in the face of climate change and the threat of extreme weather events, but in order to move forward with a plan for an innovative rebuild we must first identify and move past the factors that influenced its frailty.

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[39] Governor Rossello and President Trump official press conference in Puerto Rico on 3 October 2017

[40] "Ascertainment of the Estimated Excess Mortality from Hurricane María in Puerto Rico." *The George Washington University: Milken Institute School of Public Health*, August 2018, p. 9

[41] "Request for Federal Assistance for Disaster Recovery: Build Back Better." *Government of Puerto Rico*, November 2017, pp. 1 and 13

[42] "Sustainable Development Goals." *United Nations: Department of Economic and Social Affairs*, 2020

Building a strong and resilient grid requires major investments in time, planning, and financial resources – something the Puerto Rico Electric Power Authority failed to follow through with on numerous occasions over many years. A review of the islands guiding documents on electrical infrastructure improvement plans over the last decade reveal an apathetic utility and local government, that have repeatedly neglected to act and follow through with promises and recommendations not only of their own leaders, but also of foreign entities and subject matter experts. Its recent history of energy reform failures is embarrassing and epitomizes an administration that has been plagued by *corruption, mismanagement, failure to complete projects, and meet mandates*.

PREPA's Downfall and How We Got Here

Alarm bells began to ring in 2010 when Ernst & Young published an independent audit of the electric utility that indicated it was holding $7,400M in long-term debt, an increase of $1,625M from the year before. This suggested PREPA was operating under a yearly deficit in excess of $1,600M – a dramatic change from previous years[43]. We can see these accounting totals in Figure 1.6.

Long-Term Debt

At the end of the fiscal year 2010, 2009 and 2008, the Authority had total long-term debt outstanding of $7,587.1 million, $6,843.1 million and $7,113.8 million, respectively, comprised of revenue bonds and other borrowings.

Authority's Outstanding Debt
(In thousands)

	2010	**2009**	**2008**
Power revenue bonds, net	**$ 7,572,024**	$ 6,008,385	$ 6,162,987
Notes payable	**15,090**	834,752	950,845
	7,587,114	6,843,137	7,113,832
Current portion	**(187,368)**	(1,067,310)	(598,296)
Long-term debt excluding current portion	**$ 7,399,746**	$ 5,775,827	$ 6,515,536

Figure 1.6 – Ernst & Young 2010 Audited Financial Statement of Puerto Rico Electric Power Authority

The audit showed much of this debt was incurred through the issuance of bonds to help cover operational expenses and capital improvements, specifically listing some of the projects the utility

[43] "Audited Financial Statements Puerto Rico Electric Power Authority for Years Ending 2010 and 2009." *Ernst & Young*, 31 January 2011, p. 14

intended to initiate and their overall costs. PREPA's balance sheet shows that it borrowed more than $200M for the construction of a natural gas pipeline through the interior of the island from north to south. This would connect the LNG terminals at Peñuelas in the south, to the power plants Palo Seco and San Juan in the northern capital district. The project was called Gasoducto del Norte – Via Verde, and was presented as a way to help reduce electricity prices and diversify the energy portfolio of the island. After facing public opposition, the utility cancelled the project in 2012 and incurred the expense of accumulated interest from borrowed funds that were never used[44]. Another project that met a similar fate was a proposal by PREPA to build an offshore regasification of LNG terminal near the southern coast of Guayama to increase the transport capacity and improve the supply of gas to Aguirre power plant. After dissent from government officials between 2015 – 2017, the proposal was finally cancelled in 2018; all this after the utility had already invested millions of dollars towards its development in assessment, design, and preparation costs[45]. PREPA was never able to garner enough public support for these projects, doing a poor job of communicating the benefits that they would have provided. Albeit not very popular, these infrastructure improvements would have addressed some of the vulnerabilities in the electric system by strengthening and diversifying the fuel supply needed for the generators – a potential liability noted earlier in this paper. The Ernst & Young audit revealed that PREPA was also working to diversify their energy portfolio and were expecting to invest heavily in renewable energy for distributed generation[46] – smaller generators, more spread out, closer to load centers (an important component of a decentralized grid).

The utility was planning for this transition in large part due to a piece of legislature that was passed earlier that year, in 2010 – Act 82 of 2010 Law for Diversification through Sustainable Renewable Energy and Alternative Energy in Puerto Rico. Act 82 was a significant piece of forward-thinking legislature that mandated the island's utility diversify its energy portfolio by increasing the share of energy produced by renewable sources while also decreasing its

[44] "Puerto Rico Integrated Resource Plan 2018-2019 Draft for The Review of the Puerto Rico Energy Bureau (Rev. 2)." *Siemens: Prepared for the Puerto Rico Electric Power Authority*, 7 June 2019, p. 7-14 (178)

[45] "Puerto Rico Integrated Resource Plan 2018-2019 Draft for The Review of the Puerto Rico Energy Bureau (Rev. 2)." *Siemens: Prepared for the Puerto Rico Electric Power Authority*, 7 June 2019, pp. 7-7 – 7-9 (171-73)

[46] "Audited Financial Statements Puerto Rico Electric Power Authority for Years Ending 2010 and 2009." *Ernst & Young*, 31 January 2011, p. 75-80

dependence on petroleum (fuel oil)[47]. This law created Renewable Portfolio Standards (RPS) that required PREPA to increase its share of generation from renewable energy sources and introducing a timeline by which to accomplish this. Act 82 stated the utility would need to ramp up its use of renewable energy to meet electrical demand to *12% by 2015*, *15% by 2020*, and *25% by 2035*[48]. These figures were quite ambitious at the time considering PREPA was generating less than 1% of its electricity from renewable sources, and there were no utility-scale wind, solar, geothermal, or tidal projects anywhere on the island.

In 2009, the utility was producing 70% of its power from oil, and 15% each from natural gas and coal[49]. Fast forward to 2013 and the utility's 40th annual report indicated its fuel mix had changed to 54% oil, 28% natural gas, 17% coal, 0.4% hydroelectric, and the remaining 0.6% from other renewable sources[50]. In the span of 4 years, the utility was only able to increase their renewable energy production to a little over half a percent of the total supply. They would need to increase this figure by 2,000% in 2 years to meet its mandated obligation of 12% total generation sourced by renewable energy, according to Act 82. The 40th annual report also stated it was projecting the renewable energy supply to grow from 0.6% to 4.5% through 2018[51], supplemented by the release of a document showcasing its renewable energy projects under development, as seen in Figure 1.7.

Figure 1.7 – Puerto Rico Electric Power Authority 2013 Main Projects Overview

Out of the 9 major projects reported on (waste-to-energy plants in Caguas, Arecibo, Manati, and Moca, wind farms in Guayanilla, Arecibo, Naguabo, and Santa Isabel, and a solar farm in Guayama), only 3 were ever built – the wind farms in Naguabo and Santa Isabel, and the solar

[47] "Act No. 82 of 19 July 2010: Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy." *Commonwealth of Puerto Rico Legislature,* 19 July 2010

[48] "Act No. 82 of 19 July 2010: Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy." *Commonwealth of Puerto Rico Legislature,* 19 July 2010, p. 3-6

[49] "36th Annual Report on the Electric Property of PREPA." *Puerto Rico Electric Power Authority*, June 2009, pp. 52-4

[50] "40th Annual Report on the Electric Property of PREPA." *Puerto Rico Electric Power Authority*, June 2013, pp. 62-3

[51] "40th Annual Report on the Electric Property of PREPA." *Puerto Rico Electric Power Authority*, June 2013, p. 62

farm in Guayama[52]. Since then, not much progress has been made and the utility was never able to meet the RPS obligations set forth in Act 82 – current figures sit at 40% oil, 39% natural gas, 18% coal, and 2.3% from renewables[53].

In 2014, recognizing PREPA's inability to meet its RPS goals and follow through with promised improvements, then-governor Alejandro Garcia Padilla pushed forth a new statute aimed to better oversee the electric utility with mechanisms included to hold it more accountable. The result was Act 57 of 2014 that led to the creation of the State Office of Public Energy Policy (OEPPE) and the Puerto Rico Energy Commission (PREC). This law would serve as the legal framework to allow these two entities to operate as the utility's Regulators[54]. The change would fundamentally transform the relationship that PREPA had with the local government, whereas it had previously acted with separate decision-making authority, the OEPPE and PREC institutions would now control the decision-making process and long-term strategic objectives of PREPA. Shortly after its inception, OEPPE released a summary report in 2014 highlighting some of its key drivers (*energy conservation*, *energy efficiency*, and *energy autonomy*).

This report placed special emphasis on the need for Puerto Rico to harness its solar and wind resources so it could strengthen its sovereignty by relying less on external sources for its energy security, furthermore laying out the expectation that they were going to continue to comply with the RPS[55]. The increase of renewable energy on a larger scale had received some pushback from PREPA officials suggesting that the grid could not support the increase due to its variable nature and the impact it would have on factors such as frequency and voltage regulation. In cooperation with its new regulators, PREPA hired Siemens to conduct an independent study of Puerto Rico's grid and its ability to integrate more renewable generation.

Siemens published two studies (2014 & 2015), building off of an earlier finding from the National Renewable Energy Laboratory (NREL) in 2013[56], concluding that Puerto Rico's grid *could* in fact handle a significant increase in renewable energy assuming that they would also

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[52] "A World Class Corporation Main Projects Overview." *Puerto Rico Electric Power Authority*, 2013, p. 45
[53] "Puerto Rico Territory Profile Overview." *U.S. Energy Information Administration*, 2020
[54] "Act No. 57 of 27 May 2014: Puerto Rico Energy Transformation and RELIEF Act." *Commonwealth of Puerto Rico Legislature,* 27 May 2014, p. 103
[55] "State of the Country's Energy Situation 2014 Report." *Puerto Rico State Office of Public Energy Policy*, 28 February 2015, pp. 19-22
[56] Gevorgian, Vahan, and Sarah Booth. "Review of PREPA Technical Requirements for Interconnecting Wind and Solar Generation." *National Renewable Energy Laboratory*, November 2013

invest in the necessary protection and control equipment, enabling the flexibility to accommodate the variable nature of solar and wind energy[57]. If the utility took the initiative to invest in new protective relays, substation transformer load-tap-changing (LTC) controllers, and voltage regulators then it is believed with high confidence that PREPA could introduce up to 884 megawatts (MW) of renewable energy – approximately 25% of its total electrical demand[58]. These studies helped invalidate the excuses utility officials had been making as the reason for their inability to meet distributed generation goals, while also establishing the legitimacy of the RPS mandates and their technical feasibility. Unfortunately, before the regulators had the opportunity to implement more aggressive measures to roll out new renewable energy projects, details would emerge of further corruption and mismanagement by PREPA officials that would essentially halt any progress the local government was determined to make.

A scandal broke out in March of 2016 when a local news organization published a story alleging major corruption and financial mismanagement at PREPA by claiming that some of its officials had intentionally been overpaying fuel suppliers for low quality oil that was used in its power plants[59]. This fraud was alleged to have occurred over decades and stated officials had received kickbacks for the purchasing of fuel oil from private dealers which accounted for more than 50% of PREPA's annual operational budgets[60]. The corruption and financial mismanagement came to a head later in 2016 when the U.S. federal government enacted its own piece of legislature referred to as the Puerto Rico Oversight, Management, and Economic Stability Act (PROMESA), that laid the foundation for the federal government to take controllership of the island and its finances.

Up to this point, PREPA had continued to operate under a yearly deficit that led to the accumulation of over $9,000M of debt, serving as a microcosm for the Puerto Rico government, which had also been operating under a deficit. PROMESA formed an independent Financial Oversight and Management Board (FOMB) which uncovered that the territorial government had

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[57] "Integrated Resource Plan Volume V: Evaluation of DG Impacts on the Distribution System." *Siemens: Prepared for the Puerto Rico Electric Power Authority*, 30 September 2015, pp. 5-1 – 5-2 (111-12)
[58] "PREPA Renewable Energy Resources Integration Study." *Siemens: Prepared for the Puerto Rico Electric Power Authority*, 19 February 2014, p. 8
[59] Walsh, Mary W. "In Scandal at Puerto Rico Utility, Ex-Fuel Buyer Insists He Took No Bribes." *New York Times*, 2 March 2016
[60] Sanzillo, Tom, and Cathy Kunkel. "Multibillion-Dollar Oil Scandal Goes Unaddressed in PREPA Contract Reform and Privatization." *Institute for Energy Economics and Financial Analysis*, July 2018, p. 18

amassed financial obligations of more than $120,000M from the issuance of debt bonds and pension liabilities[61]. PREPA's accounting and business practices were further scrutinized and brought into question when it was revealed that they were subsidizing the power consumption of numerous other public institutions, allowing them not to pay for the electricity they were using and then passing the costs on to the rest of the rate payers[62]. PREPA's annual reports had highlighted the outstanding debts owed to them in accounts receivable, totaling hundreds of millions of dollars, from institutions such as the Department of Education, Aqueducts and Sewer Authority, Port Authority, Public Building Authority, Urban Train Administration, and Medical Services Administration[63].

PREPA had established a precedent where city governments, schools, transportation systems, and hospitals were practically exempt from paying for their own electricity[64]. After observing the grave mismanagement from PREPA and the local government, the FOMB put a halt to any capital expenditures and implemented measures of austerity to try and curb the impacts of running a massive deficit[65]. PREPA was on the precipice of bankruptcy, its grid in a weak and vulnerable position with no budget to replace aging infrastructure. The electric utility had demonstrated that it was in no position to manage its own organization; finally, the years of corruption, financial mishandling, inability to meet mandates, failure to follow through with plans for improvement, and listen to the recommendations of other subject matter experts had led to a catastrophic demise where it was forced to stand idle while outsiders tried to comprehend the entirety of its ineptitude. We see a similar pattern of behavior from PREPA in the way that they managed the infrastructure on the two island municipalities of Vieques and Culebra, characterized by a litany of broken promises and failure to follow through with improvements to their section of the grid.

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[61] "Final Investigative Report." *Independent Investigator Kobre & Kim LLP: Prepared for The Financial Oversight & Management Board of Puerto Rico*, 20 August 2018, p. 2

[62] Allen, Greg, and Marisa Peñaloza. "Power Problems: Puerto Rico's Electric Utility Faces Crippling Debt." *National Public Radio (NPR)*, 7 May 2015

[63] a) "36th Annual Report on the Electric Property of PREPA." *Puerto Rico Electric Power Authority*, June 2009, p. 68
b) "40th Annual Report on the Electric Property of PREPA." *Puerto Rico Electric Power Authority*, June 2013, p. 80

[64] Allen, Greg, and Marisa Peñaloza. "Power Problems: Puerto Rico's Electric Utility Faces Crippling Debt." *National Public Radio (NPR)*, 7 May 2015

[65] "Final Investigative Report." *Independent Investigator Kobre & Kim LLP: Prepared for The Financial Oversight & Management Board of Puerto Rico*, 20 August 2018, p. 108-10

PREPA's Failures with Island Municipalities

In 2011, the government of Puerto Rico's Department of Economic and Commercial Development, with cooperation and input from local grassroots organizations, published a Master Plan for the Sustainable Development of Vieques and Culebra that intended to serve as a guiding document for the island municipalities' future development. An important focus of this document was on infrastructure improvements to the electrical grid and how it could transform its system to become cleaner, more efficient, and more independent[66]. Authorities identified the vulnerable nature of the power system for these two islands and recognized that changes would have to be made in order to adequately prepare these communities for the risk of having to rely on submarine cables to meet the local demand of electricity. Recommendations were set and strategies outlined to include the construction of utility-scale renewable energy plants (wind and solar) and improvements to substations and other supplementary devices that would allow the islands to sustain their electrical demand in the event of a disruption to the submarine cables[67].

The Master Plan described how these projects would ensure the continuity of services and administration in the case of a larger blackout on the mainland of Puerto Rico, and how they would reduce the overall dependence on fuel oil in the region while at the same time reducing carbon emissions. PREPA's contingency plan in the event of a loss of power from the mainland was, and still is, to use backup generators on the island municipalities until normal service could be restored. The problem with this plan was that PREPA never completed the installation of two emergency backup generators it had brought to Culebra in 2010. These generators sat idle within Culebra's sole substation for seven years as a legal battle played out between the electric utility and the contractor hired to oversee the project[68]. The position of these idle generators from PREPA and new generators brought in by USACE are illustrated below in Figure 1.8 after Hurricane Maria.

[66] "Master Plan for the Sustainable Development of Vieques and Culebra." *Puerto Rico Department of Economic Development and Commerce*, 30 June 2011, pp. 99-104

[67] "Master Plan for the Sustainable Development of Culebra: Part III Land-Use Strategies and Implementation." *Estudios Técnicos, Inc.: Prepared for Interagency Group of Vieques and Culebra*, 27 December 2004, pp. 15-32

[68] Pacheco, Istra. "Special Report: Culebra's Energy Lifeline Threatened." *News Is My Business: Center for Investigative Journalism*, 26 April 2018

Figure 1.8 – Culebra's Substation After Hurricane Maria with Old and New Generators

PREPA never complied with the objectives of the Master Plan, nor with their own contingency plan, leaving Vieques and Culebra in a heightened state of vulnerability with regards to their electrical supply.

We see yet another instance of failure to follow through with improvements in 2014 when then-governor Alejandro Garcia Padilla enacted Law 26 of 2014 which set out a 10-year plan to transform Culebra into the first energy independent island municipality in Puerto Rico[69]. The law created a special commission for the purpose of rolling out 11 detailed initiatives that would accomplish this goal, referred to as Environmental Pioneer 10-year Plan for Culebra. The first two initiatives were to make Culebra energy self-sufficient and waste neutral, and to construct renewable energy plants, respectively. The government had earmarked approximately $10M to achieve the 11 goals, with half of that going towards the upgrade of electrical infrastructure so the grid could tolerate the planned renewable energy[70]. After building excitement around the new plan and mobilizing resources, local elections were held in 2016 which resulted in the changing of administrations. There was a new political party in charge of Puerto Rico, with a new governor and new executive directors of most public institutions[71] coinciding with the rule of the Financial

[69] "Law No. 26 of 13 February 2014: Culebra 10-Year Plan, Environmental Pioneer." *Commonwealth of Puerto Rico Legislature*, 13 February 2014
[70] "Law No. 26 of 13 February 2014: Culebra 10-Year Plan, Environmental Pioneer." *Commonwealth of Puerto Rico Legislature*, 13 February 2014, pp. 1-4
[71] Alvarado, Cindy B. "Governor-Elect Appoints OGP, ASG, AFV Directors." *Caribbean Business*, 27 December 2016

Oversight and Management Board. Sadly, work for the Environmental Pioneer 10-year Plan for Culebra went undone and was never heard from again. As a result of systemic failures to modernize infrastructure, properly manage a budget, stick to improvement plans and develop innovative projects, the island of Puerto Rico and its two island municipalities were left with high risk of, and vulnerability to, a large-scale blackout from an extreme weather event, which the island was exposed to in 2017 during Hurricane Maria. Officials had failed to understand the magnitude of their decisions in not upgrading and hardening the grid but were made quite clear of the consequences once the storm hit.

<u>Second Chances</u>

In an ironic turn of events, precisely because of Hurricane Maria and the damage sustained to the island's grid, Puerto Rico is placed in a unique position to have another chance at building a more resilient and sustainable power system. Despite past failures, Puerto Rico now has the opportunity to assemble a new grid from scratch with the help of *federal agencies and funding*, *galvanized public support and political will*, *guidance and technical assistance from international corporations*, while also leveraging the benefits of having had the time for *new technologies to mature and reduce in price*. Although the storm had produced estimated damages to the island as a whole in excess of $90,000M[72], the United Sates government decided to allocate a considerable amount of federal relief funding to help with the island's recovery efforts.

It took a few years to assess total damages and apportion the necessary funds in Congress, but in September of 2020 the U.S. government, through FEMA, awarded the island $13,000M to spend on reconstruction, with an additional $9,000M authorized for release later down the road, bringing the total financial commitment of the federal government to more than $26,000M – the only natural disasters to receive more federal funding were Hurricane Katrina and Hurricane Sandy[73]. Out of the $13,000M awarded to Puerto Rico, $9,600M was specifically reserved for PREPA and improvements to the grid. Once the island began to transition away from disaster recovery and their situation had stabilized, the U.S. government was able to provide further

[72] "Request for Federal Assistance for Disaster Recovery: Build Back Better." *Government of Puerto Rico*, November 2017, pp. 1-3

[73] a) "Three Years After Hurricane María, FEMA Obligations Reach $7.3 Billion." *Federal Emergency Management Agency*, 16 September 2020

b) "President Trump Is Supporting the People of Puerto Rico as They Continue to Rebuild Following Natural Disasters." *U.S. White House: Press Release*, 18 September 2020 assistance from federal agencies in the form of guidance, analysis, and recommendations for future actions and how best to approach the rebuilding period. The Department of Energy (DOE) made specific recommendations for the diversification and decentralization of energy sources, as well as accelerating the deployment of microgrids by establishing reasonable and attainable regulations surrounding their implementation[74]. Similar recommendations were echoed by private corporations and institutions motivated to help the island's energy transition.

Siemens prepared a report for the island's government in 2018 that analyzed the grid's ability to be broken up into 10 smaller minigrids, presented in Figure 1.9, that if needed, could operate independently of the larger grid by having their own sources of generation, automation, and control equipment[75].

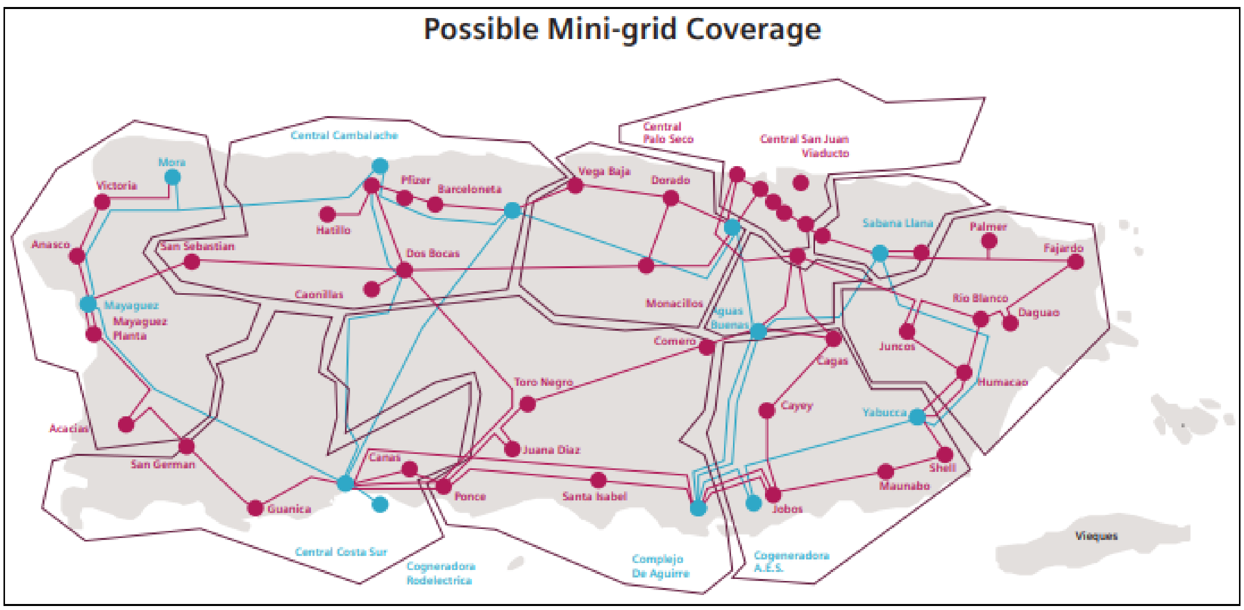

Figure 1.9 – Siemens' 2018 Proposal for Minigrid Design Puerto Rico Electric Power System

To achieve the recommended designs would require a significant undertaking since many of the minigrids do not contain any generation within their proposed footprints. Remember, that most of Puerto Rico's generation sources are located in relatively few pockets on the island, reflecting the nature of a centralized grid. The recommendations state each minigrid should be supplied by a combination of smaller fossil-fueled generators, renewable energy installations, and battery

[74] "Energy Resilience Solutions for the Puerto Rico Grid, Final Report." *U.S. Department of Energy*, June 2018, pp. 29-34

[75] "Resilient by Design: Enhanced Reliability and Resiliency for Puerto Rico's Electric Grid." *Siemens*, 2018, pp. 4-6

storage, which they opined would allow the greatest resiliency through reduced dependence on large, concentrated power plants[76]. With this model, small communities could shield themselves from the effects of traditional centralized grid disturbances that result in voltage collapse or frequency decay and cascading outages – typically leading to island-wide blackouts. Disturbances could theoretically be contained to the individual minigrids in which they occur, or in the event of a much larger disturbance, such as a natural disaster, personnel could repair the damaged infrastructure within *their* minigrid and immediately begin to supply power, not having to rely on the restoration of large faraway power plants and long-distance transmission lines.

Industry experts from a variety of institutions have published studies of PREPA's network and how it responded to Hurricane Maria, with comparable recommendations on a future rebuild. The New York Power Authority (NYPA) was one of the main organizations, along with FEMA and USACE, that were involved in the immediate restoration of power in Puerto Rico following the hurricane. NYPA also supplied the government of Puerto Rico and PREPA with a report in late 2017 that urged the island and its utility company to invest heavily in renewable energy for distributed generation, microgrids, upgrading of structures to higher standards to withstand at least Category 4 hurricanes, the burying of conductors as opposed to overhead wires, and elevation of the majority of substation elements around the coast that were susceptible to flooding[77]. NYPA estimated the overall cost to rebuild the grid in a more resilient fashion at $17,000M, most of which was allocated to the strengthening and storm hardening of 3 areas – $9,000M for T&D assets, $3,000M for large power plants, and $1,600M for substations[78]. In addition to these 3 areas, NYPA advocated the expenditure of another $1,500M towards the new construction of renewable energy and microgrids to help transition towards a decentralized system, in the belief that *microgrids* could become the key to a more resilient power system[79].

The damage from Hurricane Maria and the international community's reaction worked to galvanize the island and its government officials, who then began to release their own assessments with the goal of establishing long-term strategies to rebuild their grid and make it more resilient.

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[76] "Resilient by Design: Enhanced Reliability and Resiliency for Puerto Rico's Electric Grid." *Siemens*, 2018, pp. 4-6

[77] Puerto Rico Energy Resiliency Working Group. "Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico." December 2017

[78] Puerto Rico Energy Resiliency Working Group. "Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico." December 2017, pp. B1-3.

[79] Puerto Rico Energy Resiliency Working Group. "Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico." December 2017, pp. 35-6.

The government began by passing Act 17 of 2019 that mandated new RPS targets and set forth a requirement that PREPA create a new Integrated Resource Plan (IRP) for approval by PREC, the local energy commission. The new RPS targets state that the island will move towards achieving a renewable energy supply of *40% by 2025*, *60% by 2040*, and *100% by 2050*[80]. Act 17 lays out the expectation that the island's grid will be supplied *entirely* from renewable sources by 2050, following in the footsteps of several U.S. states (Hawaii, Massachusetts, Connecticut, Arizona, California, Florida, Virginia, etc.)[81]. Act 17 also establishes the regulatory framework to help support and develop specific industries and technologies for penetration into the grid, including renewable energy and distributed generation, as well as microgrids, and finally a component to add competition to, and privatization of, the energy markets[82].

The increase in political will, stakeholder support, federal oversight, and subject matter expert recommendations have already led to tangible improvements with the privatization of T&D operations and maintenance (O+M) work[83], as well as the roll out of Requests for Proposal's (RFP's) to develop/install large private and independent generators on Vieques and Culebra to potentially power their portion of the grid independently[84]. Aside from government support and industry expertise, the energy sector in Puerto Rico, and renewables in particular, can benefit more than ever by having had the time for these technologies to mature in terms of both cost and efficiency. If you look at Figure 1.10, you can see wind and solar technologies have made leaps and bounds over the last 10 years with the reductions in total cost and increases in capacity and efficiency, setting a trend that shows renewable energy technology becoming cheaper while also producing more energy[85].

[80] "Act No. 17 of 11 April 2019: Puerto Rico Energy Public Policy Act." *Commonwealth of Puerto Rico Legislature*, 11 April 2019, p. 23

[81] "State Profiles and Energy Estimates." *U.S. Energy Information Administration*, 2020

[82] "Act No. 17 of 11 April 2019: Puerto Rico Energy Public Policy Act." *Commonwealth of Puerto Rico Legislature*, 11 April 2019, pp. 7-8

[83] "Puerto Rico Public-Private Partnership for the Electric Power Transmission and Distribution System." *Puerto Rico Public-Private Partnership Committee Report*, May 2020, pp. 4-7

[84] "Request for Proposal (RFP79057): Electrical Power Solutions for Vieques and Culebra Islands." *Puerto Rico Electric Power Authority*, 13 April 2018

[85] "Global Trends - Data and Statistics." *International Renewable Energy Agency*, 2020

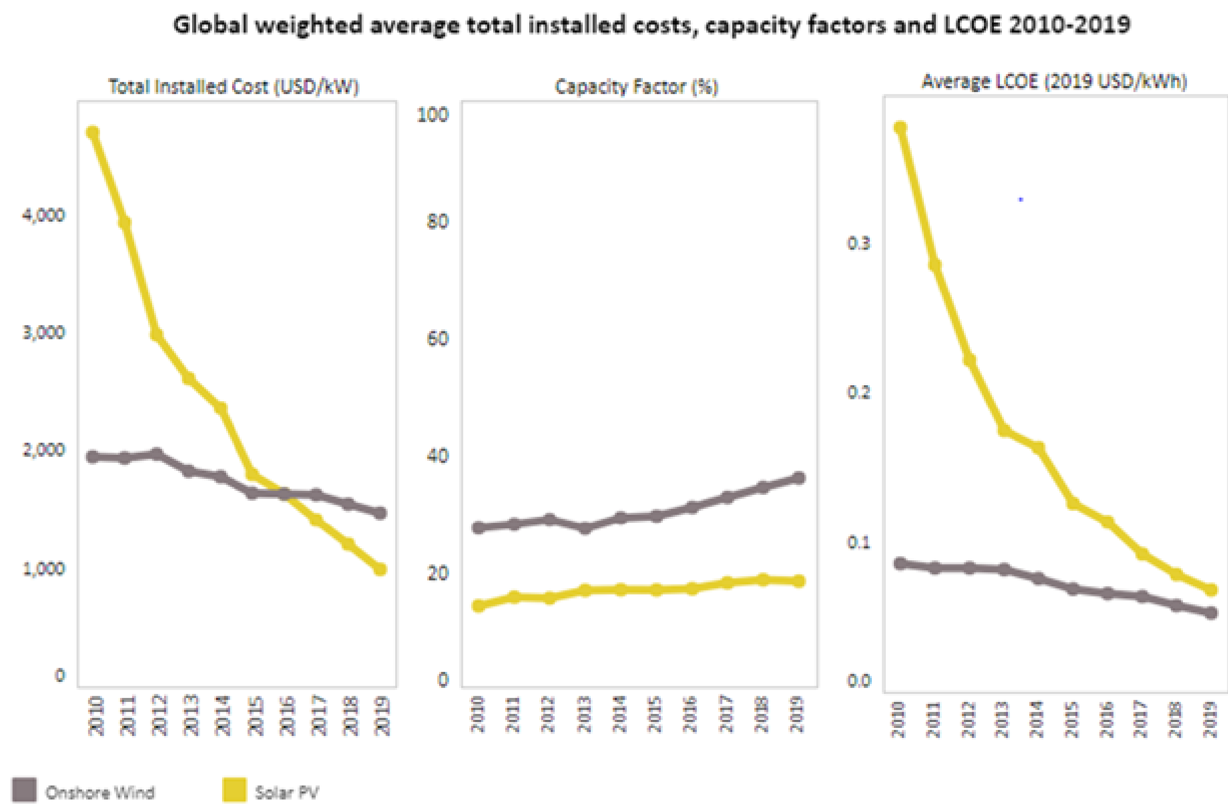

Figure 1.10 – International Renewable Energy Agency 2020 Data & Statistics: Global Trends

This trend has significantly outpaced every other energy supply technology currently used except for natural gas combined-cycle power plants, which have mostly benefitted from decreasing natural gas prices. The advances in technology create the perfect opportunity for the island to capitalize on their excellent wind and solar natural resources, for PREPA to take a leadership position during their power system rebuild and actually develop a more resilient and sustainable grid.

We can now see a combination of factors that make this a very interesting time for PREPA, and the energy landscape of Puerto Rico as a whole. The embattled electric utility, with the hindsight of having been able to observe the weak performance of their network during and after the hurricane season of 2017, share the unique wisdom of understanding they have a very brittle and unreliable grid. Yet at the same time, PREPA is experiencing unprecedented support in their efforts to rebuild from local politicians, federal agencies, and private enterprise. The time is right for Puerto Rico to harness this synergy and actually follow through with expert recommendations, so they can take full advantage of the opportunity afforded them by disaster funding and matured technology. Although PREPA has a history of failure, spanning several sectors, they have the distinctive ability to redeem themselves by leading the energy transition and assembling a decentralized grid with the rollout of renewable energy, flexible controls, and storage so the people of Puerto Rico can realize the benefits of a more reliable and resilient grid. This is a region where climate change is having a significant impact, where weather events will intensify, and a stronger grid is needed to shield the people from some of the harsher consequences felt by natural disasters in the form of damage to critical infrastructure and power loss. Nowhere is this more deserved than on the two island municipalities, Culebra and Vieques, who for decades have been petitioning to upgrade their electrical infrastructure, for the energy independence that was promised them long ago. We know it is possible, and now is the time to achieve it.

PART II

Culebra Solar Farm Project Development and Feasibility

Project Overview and Introduction

After completing an analysis of PREPA's challenges over the last 10 years and evaluating subsequent industry recommendations, we know that the island of Puerto Rico is capable of, and determined to, accelerate the development of renewable energy to supply portions of their electrical demand. Experts conclude that the island's power system can handle a much higher penetration of these technologies, such as wind and solar, and may actually be necessary in order to fortify the resiliency of the grid by decentralizing power supplies. This decentralization supports a network configuration that compartmentalizes itself into smaller micro/minigrids that would make it possible to restore power significantly faster after major disturbances to the grid, especially natural disasters. A local community that would benefit tremendously from having a [cleaner, more reliable] local power supply is the island municipality of Culebra, and in this spirit, we will be evaluating the potential to develop and install a utility-scale solar photovoltaic farm on the island. Before we examine the possibility of constructing this type of infrastructure on Culebra, we must first present a set of assumptions and limitations that we will be working from in this study due to the defined scope and preliminary nature of this paper.

There are many unknowns in this case study, and we will be working with the restriction of not knowing what the specific ampacity and cable ratings are of the two submarine lines that transport energy from mainland Puerto Rico to Vieques, and Vieques to Culebra. These are important to know for adequately sizing your solar farm and assessing the viability of exporting excess power from Culebra towards Vieques or even mainland Puerto Rico. We also do not know what the specific electrical consumption of Culebra is on a per year basis in kilowatt hours; we only know the combined yearly consumption of *both* Vieques and Culebra is 46,500,000 kWh[86] and that the peak demand of Culebra is 2.2MW[87] (the greatest amount of electrical demand at any one time). Since the capacity of the cables and yearly consumption on Culebra is not publicly available, we are working under the assumption that the submarine cables *will* be able to sustain

[86] "Master Plan for the Sustainable Development of Culebra: Part III Land-Use Strategies and Implementation." *Estudios Técnicos, Inc.: Prepared for Interagency Group of Vieques and Culebra*, 27 December 2004, p.17
[87] "Master Plan for the Sustainable Development of Vieques and Culebra." *Puerto Rico Department of Economic Development and Commerce*, 30 June 2011, p.100

the flow of any excess power away from Culebra, and within reason that the production from a 10MW solar farm will be able to supply most of, if not all, the demand on the small island.

Another limitation of this paper is that the study of energy storage (sizing and technologies) will not be explored in detail as it lies outside the scope of this analysis. Energy storage is extremely valuable in mitigating issues with voltage and frequency regulation, ramping, and transient ride-through often experienced with variable generation and must be explored further to determine a more substantive approach or design for establishing energy independence in Culebra. The modular composition of storage though, make any future evaluation relatively straightforward. Additionally, during economic projections we mention the use of current financial incentives that may change in the future or be eliminated altogether, such as the Investment Tax Credit (ITC) and Solar Renewable Energy Certificates (SREC's). Lastly, the three sites chosen for production modeling were selected based off publicly listed open plots of land for sale in Culebra at the time this study was produced and may no longer be available as potential sites for purchase or development.

We will be evaluating sites and assessing feasibility from the *Initiating* phase and process group of the Project Management discipline, and thus from this point of view we are only considering preliminary analysis of such a project and if it is worth exploring in more detail[88]. Since our primary objective is to better understand the probability of successfully initiating and building a solar farm on Culebra, we will be conducting more of an analysis on topics such as natural solar resources, production modeling, business case, and market forces, and *not* the implementation of this endeavor, so we will not be covering topics that list specific vendors, procurement strategies, logistics, schedule timelines, or cost breakdowns. An examination was made under the guidance of a project charter that defined success as *'the construction of a 10MW solar photovoltaic farm that contributed to the reliability, resiliency, and energy independence of Culebra, was profitable in nature, had minimal ecological impact, and directly benefitted the local residents.'*

[88] *"A Guide to the Project Management Body of Knowledge (PMBOK® Guide)."* 6th ed. Newtown Square, Pa.: Project Management Institute, Inc, 2017, pp. 561-64

Natural Solar Resources and Irradiance

Utilizing two independent and reputable satellite sensing solar natural resource data bases we are able to conclude that Puerto Rico, and Culebra in particular have remarkable, above average solar irradiance resources – at approximate coordinates of 18° latitude, -65° longitude. We see on Figure _____'s left hand side information from World Bank sponsored SolarGIS site that displays Global Horizontal Irradiance (GHI) occurrence on Puerto Rico and Culebra, reporting kilowatt hours per square meter (kWh/m²) both in terms of daily and yearly averages in excess of ~6 and 2,115 respectively[89]. We confirm this using Figure 2.1's right hand side graphs, taken from NASA's Langley Research Center Power Data Access Viewer tool indicating that the daily GHI totals range from 4 to 7 on average with slight variability throughout the year as the seasons fluctuate, experiencing 7 kWh/m² the most with just under 80 days out of the year[90]. GHI is the single most effective parameter used to assess natural solar resources and solar production potential at any particular site[91]. The two data base sets mentioned earlier signify exceptional resources with minimal variability in Culebra, making it an ideal location for photovoltaic technology.

[89] "Prospect Solar Global Horizontal Irradiance GIS Viewer." *SolarGIS*, 2020

[90] "Power Data Access Viewer: Prediction of Worldwide Energy Resources (Coordinates 18.18, -65.16)." *NASA Langley Research Center*, 2020

[91] a) Neill, Susan, et al. "*Solar Farms: The Earthscan Expert Guide to Design and Construction of Utility-Scale Photovoltaic Systems*." New York, Ny.: Routledge, 2017. p.55

b) "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide." *International Finance Corporation (World Bank Group)*, 2015, p. 44

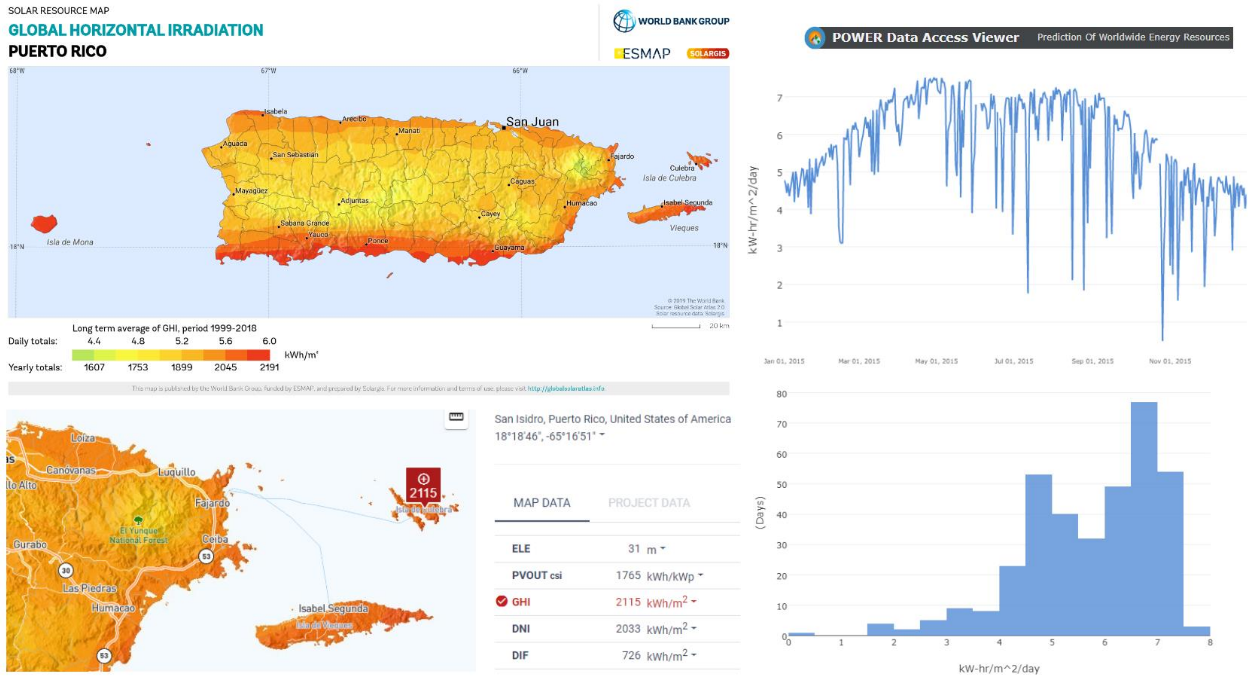

Figure 2.1 – Natural Solar Resources in Puerto Rico. Left Half: GHI Data from SolarGIS Prospect Map | Right Half: kWh/m² Data from NASA Langley Research Center Power Data Access Viewer Tool

Site Selection

Three local sites on Culebra were selected to perform production modeling calculations and forecasting. These sites were chosen from a list of publicly available open plots of land for sale, accessible via internet from a variety of real estate sources. Locations with 30+ acres of available land were preferred due to the area requirements for solar photovoltaic installations, on average requiring approximate 3 acres to develop a 1MW installation[92], thus 10MW solar farm would require 30+ acres to build. The sites are relatively equidistant to the lone substation on Culebra, of which any development would need to interconnect with – all 3 sites averaging about a two-mile distance travel to the substation, using existing roads through which to construct a path. You can see each site's relative geographic position to the substation, as well as to each other in Figure 2.2. A quick summary of these plots is provided below next to the Figures for each parcel.

[92] "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide." *International Finance Corporation (World Bank Group)*, 2015, pp. 59-60

Figure 2.2 – Bird's Eye View Culebra Island with Proposed Solar Photovoltaic Sites and Substation

Site 1 - Barrio Frailes

Figure 2.3 – Frailes Land Boundary

Site 1 is located in the **Frailes** neighborhood of Culebra, situated on the eastern end of the island just north of Honda Bay, its perimeter drawn in red almost a horizontal rectangular shape seen in Figure 2.3. The plot encompasses a total of 31 acres and is for sale at $2.8M[93]. The land itself is open, free of obstructions and any major vegetation aside from small shrubbery, with a slight slope in tilt facing north about 25°. The site is also next to a major access road of the island – Road #250, making the land rather accessible.

[93] "32 Cuerdas (31 Acres) Barrio Frailes Culebra." *Clasificados De Puerto Rico Online*, 2020

Site 2 - Barrio San Isidro

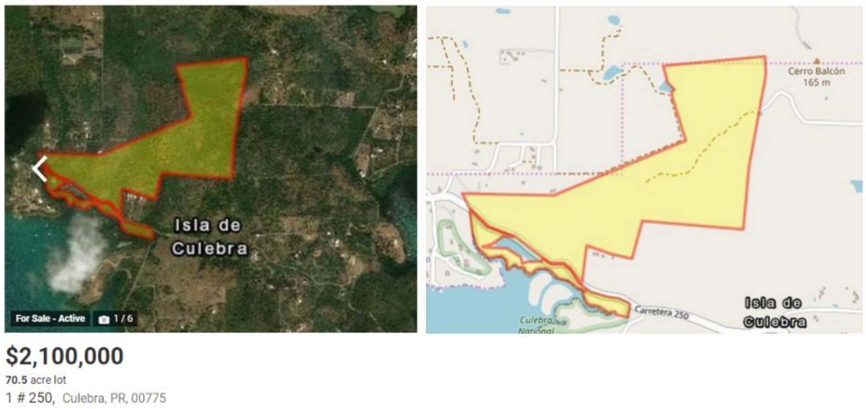

Figure 2.4 – San Isidro Land Boundary

Site 2 is located in the **San Isidro** neighborhood of Culebra, sitting just a few hundred feet northwest of Site 1 in Frailes. The property lines show an atypical boundary, most closely resembling a left facing boot, seen in Figure 2.4. The plot encompasses a total of 70 acres and is for sale at $2.1M[94]. The land is free of major obstruction and also nestled along major access Road #250. The land sits within a small valley characterized by a slight slope, southwardly facing at a tilt of about 20°.

Site 3 - Barrio Playa Sardinas

Figure 2.5 – Playa Sardinas Land Boundary

Site 3 is located in the **Playa Sardinas** neighborhood of Culebra, situated on the southeastern portion of the island, south of Honda Bay. The property holds a similar rectangular shape as the land at Site 1, with a 60° angle at its base pointing west, or having an azimuth of 210° as seen highlighted in blue in Figure 2.5. The plot encompasses a total of 39 acres and is for sale at $1.2M[95]. This land is also free of major obstruction, sits along route Playa Sardinas II, and may be the least visible of the three sites as it lies in the southeast quadrant of the island facing mostly south away from any residential developments. Much of the terrain at this site slopes southwardly at 30°.

[94] "# 250, Culebra, PR 00775." *Realtor.com*, 2020

[95] "Lot #26 - Bo Playa Sardinera." *Island Realty: Culebra, Puerto Rico*, 2020

Production Modeling

With the use of cloud based solar design and production modeling software, we were able to simulate with a moderate degree of accuracy the estimated electrical production capability of solar farms at each site utilizing similar conditions and technologies but taking specific land properties into account. The conditions we used across each site include same capacity solar panels and inverters, and the same Inverter Loading Ratio (ILR), or DC/AC ratio. Each site was designed to have 28,800 350W solar panels, connected to 162 50kW inverters. This configuration represented a total DC nameplate capacity of 10.1MW and an AC capacity of 8.1MW, which equates to roughly a 1.24 ILR – the optimal ratio by most sizing standards[96]. The azimuth, tilt, and shape of solar panel array layouts were adjusted slightly to correspond to the natural landscapes of each site, dictated by the sloping terrains and property boundaries. After designing the systems and incorporating the different values for each parameter in solar modeling software program HelioScope, we ran the them through simulations in the program to calculate estimates of yearly production totals. To validate these estimates, we compared them with simulations run in PVWatts, an independent preliminary analysis program built by NREL, which calculated its own set of yearly production figures. We found similar production estimates across both platforms, displaying consistent results for each site. The variability between programs yielded a delta of between 100,000 – 300,000 kWh/year and predicted system losses of 5-7%. The yearly production totals of kilowatt hours produced for each site on Culebra are listed below in Figure 2.6. **For more detailed information regarding design components, monthly breakdown, system losses, one-line diagrams, and array characteristics see Appendices A-C**.

Location	**HelioScope Production Est. (kWh/yr)**	**PVWatts Production Est. (kWh/yr)**
Site 1 Frailes	14,038,555	13,693,421
Site 2 San Isidro	14,984,300	14,790,004
Site 3 Playa Sardinas	14,621,100	14,528,560

Figure 2.6 – HelioScope and PVWatts Production Modeling Results

[96] a) Fiorelli, Jon, and Michael Zuercher-Martinson. "Supersize It: How Oversizing Our Array-to-Inverter Ratio Can Improve Solar-Power System Performance." *Solar Power World*, no. 7, 2013, pp. 42–46. *Inverter Insider*.
b) "The Ideal Inverter Loading Ratio (ILR) for Commercial and Utility Solar Plants." *BlueOak Energy*, 18 November 2015

Business Case

In order for most development projects to be successful and sustainable, especially ones undertaken by private enterprise, they must make business sense and be justified economically. The projects must sustain themselves financially and even have some rate of return comparable to other investment strategies in order to motivate organizations to develop and build these types of infrastructure projects. No entity, aside from perhaps government, will proactively initiate or move forward with a project that will knowingly result in a financial loss. So, working with this framework, we must evaluate the potential economic implications of building a solar farm on Culebra and decide whether it will sustain itself and even generate enough revenue to make a reasonable return on investment. To complete an initial calculation, we must assess the project's possible costs and revenue, using the information we have and the production modeling we completed previously.

We can sum up total costs associated with utility-scale solar photovoltaic projects by utilizing industry assumptions commonly deployed during preliminary assessments. These assumptions typically apply a dollar value to every watt constructed, referencing industry average costs in dollars per watt ($/W) that can then be scaled up and applied to the size of your proposed system. This dollar figure includes the costs associated with the solar panels, inverters, balance of plant (BoP) components, engineering procurement and construction (EPC), and other ancillary expenses. The total cost to install large solar systems has steadily decreased over the last 10 years, coinciding with a drop in the cost to manufacture solar panels, and current industry estimates place that cost at about *$2 per watt*[97].

A recent NREL study that looked at energy resilience options for Culebra states that after speaking with several solar developers in Puerto Rico, they were able to determine and settle on an average cost of *$2.15 per watt* ($2.15/W) and this is the figure we will use in our financial calculations[98]. Next, we will multiply this figure by DC nameplate capacity of our proposed system – the DC capacity of our HelioScope designs are 10.1 million watts, so 10.1 million multiplied by $2.15 comes out to *$21.715M*, the cost to theoretically construct our proposed solar farm on the island of Culebra. If we apply a cost of $16 per kilowatt for operations and maintenance (O+M)

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97 Neill, Susan, et al. "*Solar Farms: The Earthscan Expert Guide to Design and Construction of Utility-Scale Photovoltaic Systems*." New York, Ny.: Routledge, 2017. p.64

98 Salasovich, James, and Gail Mosey. "Energy Resilience Assessment for Culebra, Puerto Rico." *National Renewable Energy Laboratory*, June 2019, p.8

expenses[99] (our overhead), and then multiply that by the project lifecycle, we get a total operational expense of *$4.04M* over 25 years. When we add the costs to develop and operate the solar farm over a 25-year period, we come up with an estimated total cost of **$25.755M**. After applying the individual costs of the land for each site, we see that total cost estimates climb to **Site 1 Frailes – $28.555M**, **Site 2 San Isidro** – $**27.855M**, and **Site 3 Playa Sardinas** – $**26.955M**.

Now that we have preliminary indicators of what the total cost may be to build one of these systems on Culebra, we will calculate the potential revenue we may generate by constructing the solar farm. Most renewable energy installations generate revenue by entering into a long-term contract with an offtaker, or a purchaser, of the electricity that your system produces. For utility-scale systems, these are most often the local electric utility, or PREPA in our case, and are applied through the execution of a Power Purchase Agreement (PPA). PPA's are used as legally binding contracts that reduce overall risk to the developers and financiers of these projects by providing the security of long-term revenue projections. They state what price the developer has agreed to sell, and the electric company has agreed to pay, for every kilowatt hour produced by the installation, typically for every year of the contract. Historical records show PREPA's past PPA's with solar developers in the range of $0.11-$0.14 cents per kilowatt hour[100], and thus we will use **$0.12/kWh** as the basis for our long-term revenue projections, as these also align with current estimates of the levelized cost of electricity (LCOE) for renewable energy projects[101]. These long-term projections are applied to each site in Figure 2.7.

Location	Production Est. (kWh/yr)	Yearly Revenue Est.	Total Revenue Est. with 25-year PPA
Site 1 Frailes	14,038,555	$1,684,627	$42,115,665
Site 2 San Isidro	14,984,300	$1,798,116	$44,952,900
Site 3 Playa Sardinas	14,621,100	$1,754,532	$43,863,300

Figure 2.7 – Preliminary Financial Calculations of Potential Revenue

[99] Salasovich, James, and Gail Mosey. "Energy Resilience Assessment for Culebra, Puerto Rico." *National Renewable Energy Laboratory*, June 2019, p. 10

[100] "Integrated Resource Plan: Appendix 3 Renewable Energy Project Status." *Puerto Rico Electric Power Authority*, December 2018

[101] NREL LCOE calculator and Solar Farms – Earthscan expert guide to design and construction of utility-scale PV systems p. 64

For simplicity's sake, we will not account for escalation clauses or diminishing production from solar panel degradation in our PPA estimates with reference to revenue collection and system production, respectively, over an assumed 25-year lifecycle with the understanding that these variables are likely to cancel each other out over the duration of the contract. Since we are not using compounding quantities like revenue escalation and degradation, we will employ Return on Investment (ROI) and Simple Payback Periods to carry out rudimentary financial calculations to assess the feasibility of each site. See Figure 2.8 for a breakdown of these categories for all three sites.

Location	**Return on Investment**	**Simple Payback (years)**
Site 1 Frailes	47.49%	16.95
Site 2 San Isidro	61.38%	15.49
Site 3 Playa Sardinas	62.73%	15.36

Figure 2.8 – Preliminary Financial Calculations of ROI and Payback Period

After applying the data from the simulations to cost and revenue projections, one can easily interpret based off these calculations that developing a solar farm on Culebra would make solid business sense; the figures we see from the ROI and Payback Period are quite lucrative and outperform investments in other sectors like the stock market or real estate[102]. Although these estimates indicate profitable returns from the development of a large solar farm, it should be approached with caution and used only as the starting point for more thorough and detailed calculations involving additional variables. For example, with our cost and revenue projections, we have not taken into account the impact of available incentives for renewable energy projects such as the U.S. federal Investment Tax Credit (ITC) which can be leveraged to reduce the overall cost of developing your project by up to *26%*[103]! Another potential incentive that could be explored further is the issuance of Solar Renewable Energy Certificates (SREC's) that solar energy infrastructure can accumulate based off production totals, and then sold at a later date to utilities trying to comply with RPS mandates[104]. Alternatively, just as we have not included some potential revenue streams, we have also left out some areas of expense that can be accrued by projects of

[102] a) "U.S. Market Activity Indexes." *Nasdaq*, 2020
b) "Office of Policy Development and Research: National Housing Market Summary." *U.S. Department of Housing and Urban Development*, 2020
[103] "Solar Investment Tax Credit (ITC)." *U.S. Solar Energy Industries Association*, 2020
[104] "Solar Renewable Energy Certificate (SREC) Trade Market." *Superior Clean Energy Management*, 2020

this magnitude. Due to the highly variable nature of some expenses, we have left topics such as *substation upgrades*, *taxes*, *local charitable contributions*, and *decommissioning* costs out of our equations.

Market Analysis

The energy landscape in Puerto Rico has had quite a turbulent history characterized by a litany of controversy, though where there is instability there is also opportunity. We have seen proposals for many projects in the territory come and go, often with the result of failure to break ground, but with the foresight to look ahead and consider the trajectory of the industry and the transformation PREPA is undergoing, one can see that there is definitely an opening to get involved and enter the energy market in Puerto Rico. Ever since the hurricanes of 2017 we have been witnessing a major shift in the public discourse on energy policy and the way it will eventually be implemented. There is tremendous political will on the island to improve their electrical infrastructure, anchored by global criticisms of past administrations, management of the power system, and how vulnerable it was to natural disaster.

Under the guidance of the federal Financial Oversight and Management Board (FOMB), local leaders have been championing the need to develop and install more resilient energy infrastructure and at unprecedented levels. Responding to Siemens' 2018 recommendation of creating minigrids, powered in part by renewable energy, the island has been focusing on efforts to finalize an Integrated Resource Plan (IRP) for PREPA that emphasizes the rollout of solar and wind energy. The final version of this IRP will look to expedite the permitting of large-scale renewable energy projects, reduce barriers to entry, and offer financial incentives and tax breaks for developers looking to build these projects[105]. The demand and appetite for renewable energy and microgrid technology is certainly growing stronger. A proposal for a utility-scale solar farm on Culebra, marketed as a driver of growth for the island and the cornerstone of its energy independence, would be positively received and align with current sentiments on energy reform.

The resident population on Culebra is very ecologically conscious and having had to deal with resource scarcity and dependence on outside forces, have become accustomed to managing local issues through the lens of sustainability. The population understands what type of changes in

[105] "Review of the Puerto Rico Electric Power Authority Integrated Resource Plan." *Government of Puerto Rico Public Service Regulatory Board of Puerto Rico Energy Bureau*, 24 August 2020. pp. 100-35 and 260-70

energy infrastructure are needed to reach the goal of independence, and as long as construction efforts are contained and have minimal disruptions to the local environment, it is the belief that the people of Culebra would support a project of this nature and magnitude. It could serve as a source of revitalization for a group of people increasingly fatigued by failures of the local electric company, and further catalyze the movement towards cleaner, decentralized power supplies. There have been failed clean energy projects on Culebra in the past and it will be important to include the local population early on in any development plans so as not to alienate them, as was experienced previously with an onshore wind power proposal[106]. Transparency is a key component for success when working with local stakeholders on developing infrastructure projects in their communities. It will be necessary to work closely with several stakeholders during the development of this project and analyzing their receptiveness to these types of endeavors is one of many indicators that reveal whether the market is suitable to build a solar farm.

After gauging whether the local residents would support a solar farm on Culebra, the first stakeholder you must develop a relationship with is PREPA. You will need to work with them from the very beginning of the project up until the very end, and even beyond as they will be the primary offtaker of the energy you produce. The PPA will be the single most important document that you must obtain and will become the foundation of your project[107]. It will dictate many elements, especially outside funding, and may contain the scope, requirements, lines of demarcation, and revenue structure of the solar farm so it will be crucial to develop a strong relationship with PREPA from the very beginning of your project during the initiating phase. The PPA will likely coincide with an Interconnection Service Agreement (ISA) that deals with all of the technical aspects of the infrastructure and will authorize you to connect to their transmission system. PREPA will also be responsible for carrying out engineering studies before the project can be built, as well as the commissioning and acceptance testing when the solar farm is ready to come online. They will hold an integral role in the development of any energy project in Puerto Rico, and although past executives have made questionable decisions, the field engineers and planners tasked with these jobs are generally very skillful and thorough.

[106] "Flamenco Wind Farm a No-Go." *National Wind Watch Puerto Rico*, 13 May 2013

[107] "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide." *International Finance Corporation (World Bank Group)*, 2015, p. 44

The U.S. Army Corps of Engineers (USACE) may have to get involved as well, depending on the proximity of the solar farm to past military installations as there were several on Culebra, so as to certify that the area is clear of old munitions[108]. In addition to PREPA and the USACE, a variety of regulatory and environmental organizations will have to approve and sign off on this type of project. The major governing body for development activities on Culebra is the Conservation and Development Authority of Culebra (ACDEC); they will have to be engaged early and convinced this project will benefit the local population before approving your project and supplying the local permits. A development plan must contain a solid Environmental Impact Statement (EIS) that address ecological impacts to the area, and any remedies to mitigate them. ACDEC is most concerned with the economic development and environmental sustainability of the island (ecotourism is the main economic driver), so they must be persuaded that a solar farm will contribute positively to the local economy, through jobs or yearly financial contributions, and will not destroy the environment. The Board of Environmental Quality (JCA) and the Department of Natural Resources and Environment (DRNA) will also have to endorse your EIS and support your proposal before it can gain approval. These two entities are primarily focused on environmental impacts and considering there are not many sensitive specimens on the island, aside from nesting sea turtles, it should be relatively simple to accommodate impacted flora and fauna.

The competitive landscape in renewable energy sector is moderate in Puerto Rico, with a mix of local and foreign companies having a foothold in the territory. Many U.S. based clean energy companies have chosen Puerto Rico as a preferred location to open regional headquarters as they try to enter the Caribbean market. These larger development companies often partner with local installers to construct their projects, and this is no different in Puerto Rico. Led by a strong and competent renewable energy business association (ACONER)[109], Puerto Rico is home to a variety of highly qualified engineering, procurement, and construction (EPC) companies and local installers. These companies and business association should be considered as collaborators, and not necessarily competitors. The engineering and construction disciplines on the island host a large consortium of qualified contractors, bolstered by the University of Puerto Rico – Mayaguez, a world-renowned educational institution and global leader in those disciplines. Through local

[108] "Defense Environmental Restoration Program & Formerly Used Defense Sites: Culebra, Puerto Rico." *U.S. Army Corps of Engineers*, 2020
[109] "ACONER: Who We Are." *Puerto Rico Association of Renewable Energy Consultants & Contractors*, 2020

publications and news reports, you can see that these market participants are turning into high gear and preparing themselves for the ramp-up in renewable energy projects, as local sentiment mirrors global trajectory of these technologies and projects.

Recommendations

The results of our preliminary analysis, when interpreted holistically, express generally favorable conditions in which to develop a 10MW solar farm on the island municipality of Culebra. Exceptional solar irradiance and available land resources helped produce encouraging production estimates from the modeling programs utilized. These estimates indicate a 10MW solar farm on Culebra would produce roughly the equivalent of all energy consumed on the island, using the rationale that both Vieques and Culebra consume 46,500,00 kWh's annually and Vieques is 4 times larger than Culebra, so Culebra would consume approximately 10,000,000 kWh's every year. Paired with an energy storage technology, a solar farm of this size could theoretically power Culebra and enable the energy independence of the island. The electrical interconnection of the 10MW solar farm would also fit nicely with current and proposed network configurations of the power system as seen in Figure 2.9, aligning with the eastern/northeastern portion of each design.

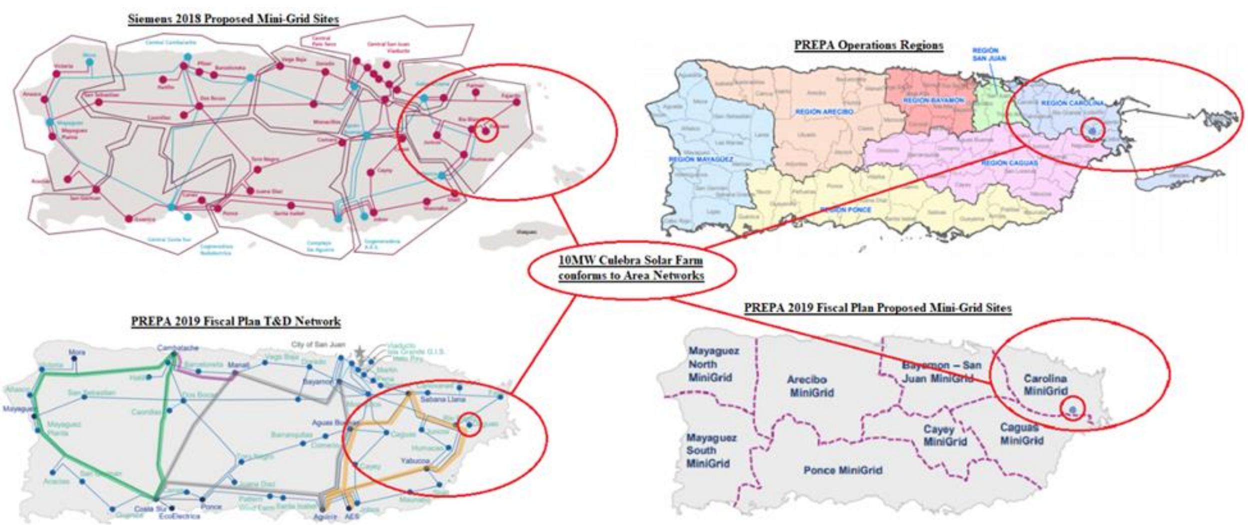

Figure 2.9 – Various Power System Configurations Highlighting Connection Point for Submarine Cable to Vieques at Daguao Substation Conforming to Eastern Quadrant of all Maps

Simplified financial calculations using production estimates and historical PPA compensation figures also suggest that this type of project on Culebra would be profitable. We have good reason to believe that a private developer can benefit from local market forces and stakeholder sentiment. Attractive financial incentives and possible tax exemptions create a lucrative environment in which to initiate a solar farm infrastructure project, supplemented by low barriers to entry and a mostly collaborative and welcoming clean energy industry on the island. The utility company PREPA, local politicians, industry experts, and resident populations now understand the need to rebuild and decentralize the power system in Puerto Rico, and the inevitable role that renewable energy will play in that transition. Although our investigation found the possibility of developing a solar farm on Culebra to be quite promising, this information must only be used as a starting point from which to dive deeper. To conclude our evaluation, it is our judgment that the development of a 10MW solar farm on Culebra has the potential to be a profitable and beneficial venture, yet more research is needed before any significant investment is made. More precise financial calculations need to be completed that include compounding variables such as taxes, incentives, depreciation, revenue escalation, and solar panel degradation. PREPA must also be consulted to determine what current infrastructure capacity is and what substation upgrades may be needed. At this go – no go junction though it is recommended that the construction of a 10MW solar farm on Culebra proceed with further investigation as preliminary results show favorability.

PART III

Project Implications and Considerations for the Future

Culebra as a Demonstration

Understanding that a utility-scale solar farm is technologically and economically feasible for the small island municipality of Culebra, we can begin to think about what impacts such a structure may have on the surrounding region if it were to be constructed. The successful installation and operation of a solar farm on Culebra could serve as a demonstration for nearby islands that the concept of variable generation and renewable energy is not only achievable, but practical in an area served with abundant natural resources such as solar irradiation and sustained wind speeds[110]. These natural resources coupled with favorable economic costs highlight the efficacy of using these types of technology to sustain local power systems. Although we did not include the separate caveat of energy storage in our earlier plans and designs (for simplicity's sake), this is an area that would need to be explored further to truly realize the benefits of energy independence.

The study and comparison of energy storage technologies will need to take place at the local level as they will depend on characteristics associated with the region and landscape in which they are being considered. These characteristics include variables such as temperature, topography, and local technical expertise. For example, we see with the Canary island of El Hierro that the topography supports the use of pumped hydro as a storage technology with its mountainous terrain. The island has constructed a pumped hydro facility atop an elevated basin that holds a large reservoir where water is pumped into with the use of excess wind energy, which is then allowed to drain via gravity and power a generator during times when the wind is not blowing[111]. While there are several examples of small islands using renewable energy technologies (some with storage), the installation of such on the island of Culebra would help to solidify the technology's legitimacy, especially in the Caribbean region which is still highly dependent of foreign oil and gas imports for electricity generation.

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[110] "Puerto Rico Territory Profile Overview." *U.S. Energy Information Administration*, 2020

[111] "The Sustainable Island." *Government of the Canary Islands: El Hierro*, 2020

It would be reasonable to believe that Culebra's use of large-scale renewable energy could encourage neighboring islands to seriously consider the idea of adopting similar infrastructure, in the sense that it could serve as a catalyst for the region and even the possibility of initiating some type of domino effect. The Caribbean region is poised to transition to renewable energy for its electricity supply, and the with the use of advancing storage technologies, could really achieve significant increases to overall resiliency in the face of a changing climate. This would also strengthen island nations' autonomy by reducing or eliminating dependence on foreign energy sources to power their grids, helping shield local economies from fossil fuel price volatility in the process. A close neighbor of Culebra that would also benefit from the deployment of renewable energy is Vieques, Puerto Rico's other island municipality.

Keeping the Momentum with Vieques

Vieques lies approximately 10 miles southwest of Culebra and is home to a population of 9,000 residents. As previously discussed, the island receives its electrical power from mainland Puerto Rico via submarine cable and has been susceptible to failure in the past. Vieques displays similar conditions to Culebra that would make it an ideal location for distributed generation and microgrid application. The major difference though between the two island municipalities is the sheer size of Vieques, which surpasses Culebra by 40 square miles. Two thirds of the island of Vieques is currently designated as wildlife refuge and is uninhabited. These eastern and western portions of the island were once used as U.S. military bases and training grounds for explosive ordinance resulting in some contamination of the land. These areas are undergoing cleanup efforts by federal agencies and thus explain why they are mostly off limit to residents of the island and are zoned for wildlife[112]. When all unexploded ordinance is secured and removed, these sites would make excellent locations for brownfield redevelopment efforts, especially renewable energy installations.

The island could use this area of roughly 14,000 acres[113] to generate a clean supply of power which it could then export to mainland Puerto Rico or Culebra under existing transmission paths. The proposed installation on Culebra could help motivate Vieques to repurpose their brownfields into usable assets that would generate reliable energy and local jobs, contributing to

[112] "Environmental Restoration Former Atlantic Fleet Weapons Training Area - Vieques, Puerto Rico." *U.S. Navy: Naval Facilities Engineering Systems Command*, 2020
[113] "Area Calculator: Vieques." *Map Developers*, 2020

the sustainability of the island. The modular nature of renewable energy and storage technologies make it easier to scale up than traditional fossil fuel power plants, allowing for the gradual growth and economic funding of these renewable energy farms over the long-term. Just as a potential solar farm on Culebra might help accelerate the deployment of renewable energy on nearby islands, it may also contribute to the more robust adoption of, and transition to, a cleaner power system in general with regard to the development of offshore wind energy in the region.

Offshore Wind Energy Development

The next major shift in the U.S. energy sector is the adoption of offshore wind. The U.S. Bureau of Ocean Energy Management (BOEM) has been soliciting requests for proposals and awarding leases for blocks of offshore land to several wind energy companies for the development of large-scale wind energy installations, shown in Figure 3.1[114].

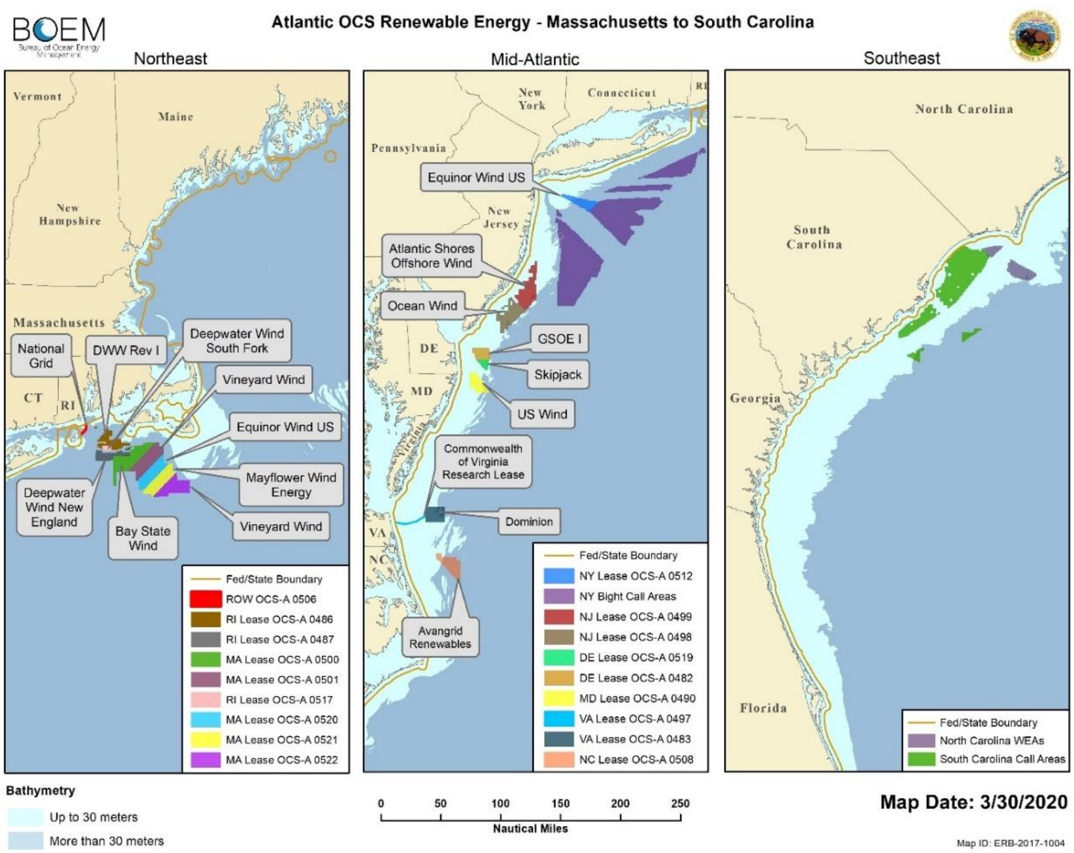

Figure 3.1 – Bureau of Ocean Energy Management Lease Agreements for Offshore Wind Developments in the North Atlantic

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[114] "Renewable Energy Maps and GIS Data: Wind Planning Areas, Wind Energy Areas and Leasing Areas." *U.S. Department of the Interior Bureau of Ocean Management*, 2020

Wind energy companies have already signed PPA agreements with electric utilities in several east coast states, ensuring offtakers for the electrical energy produced by these wind farms[115]. Offshore wind is by far the most likely renewable energy technology to replace baseload fossil fuel power plants for electrical demand in the near future due to the capability of installing larger turbines and having steadier wind supplies offshore. The special relationship that the U.S. shares with Puerto Rico could become advantageous for the small island in this scenario, with the availability of, and proximity to, U.S. wind energy experts and financial institutions to help guide the exploration of this technology for Puerto Rico. Again, the successful installation of a utility-scale solar farm on Culebra would further legitimize a transition towards renewable energy, also signaling to the U.S. that the government of Puerto Rico is serious about diversifying their energy supply, and have the political will and local support for these types of projects. Another logical step in the evolution of electric power systems in the Caribbean region would be to explore the concept of interconnecting and synchronizing several island grids together through the installation of submarine power cables to share the benefits of large-scale dispersed renewable generation.

Interconnection and Regional Transmission Networks

There have been focused efforts over the last 15 years to assess the viability of connecting Caribbean power grids through submarine cables, essentially consolidating various electrical apparatus that would then become available to areas where they are most needed, even neighboring islands[116]. We already see this configuration with the power grid in Puerto Rico, linking Vieques and Culebra's electrical networks to mainland Puerto Rico. Due to Puerto Rico's experience with submarine transmission, as well as the advanced nature of their electrical infrastructure (comparatively speaking, with other parts of the Caribbean), most studies have centered around designs that link Puerto Rico's power grid with that of the U.S. Virgin Islands (USVI). Two of the three USVI's have been identified as being ideal candidates for interconnection via submarine cable with mainland Puerto Rico – St. Thomas and St. John; unfortunately, the depths of the Virgin

[115] Beiter, Philipp, Paul Spitsen, Walter Musial, and Eric Lantz. 2019. "*The Vineyard Wind Power Purchase Agreement: Insights for Estimating Costs of U.S. Offshore Wind Projects*." February 2019
[116] "The Project: Reliable, Cleaner, and Lower-Cost Power for the Caribbean." *CARITrans*, 2020

Island Basin (sea trench where depths reach ~2,000 meters[117]) make an interconnection with St. Croix unfeasible, as seen in Figure 3.2.

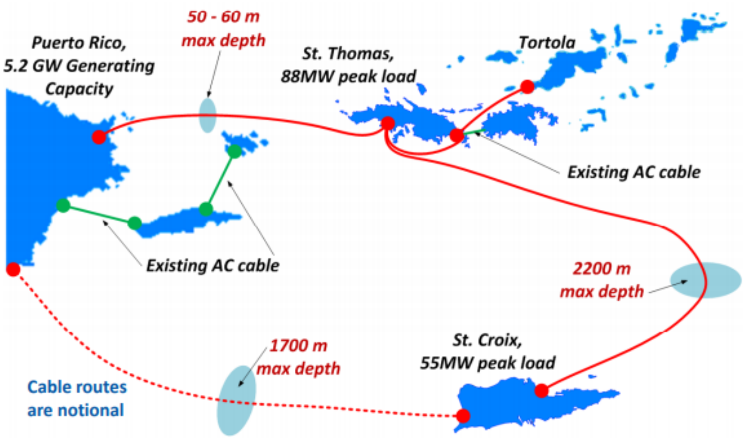


Figure 3.2 – National Renewable Energy Laboratory 2011 Proposed Design for Inter-Island Transmission Connection: Puerto Rico and U.S. Virgin Islands

St. Thomas and St. John share geopolitical ties with Puerto Rico, are of close physical proximity, and have relatively low overall electrical demand that have made them the prime targets for study. Major benefits of sharing electrical tie-lines between these two territories include the socialization of spinning reserves, excess capacity, voltage and frequency regulation, greater penetration of renewable energy, and strengthened telecommunication channels through submarine cables that encompass both power and fiber lines[118]. All of these benefits would serve to improve the reliability and resiliency of the network by creating more transmission paths and increasing access to more generating units. If there is an electrical disturbance to any one area of the grid, redundant paths and diversified options would help alleviate the condition by reducing or avoiding stress on other parts of the system. The interconnection of electrical networks may also encourage multilateral cooperation and international relations in the region.

Interconnections are not without their limitations though, and just as they may encourage cooperation, they may also be a source of contention and disagreement. In order to operate power grids, there must be a single point of authority that dictates the flow and balancing of power assets. In this respect, an interconnection between two separate entities would necessitate the creation of an Independent System Operator (ISO), or a single governing body that controls and manages the flow of power. Although decision-making teams at the ISO can be comprised of individual's from

[117] Liu, Hanlin, and Guoquan Wang. "Relative Motion between St. Croix and the Puerto Rico-Northern Virgin Islands Block Derived from Continuous GPS Observations (1995–2014)." *International Journal of Geophysics*, vol. 2015, 27 August 2015

[118] Gevorgian, Vahan. "Renewable Energy and Inter-island Power Transmission." *National Renewable Energy Laboratory*, 6 May 2011, pp. 27-33

all territories, there may still arise disagreement around which generating assets to bring online, and which directions to move the power, often having economic implications that may favor one territory over the other, coincidentally[119]. Other challenges to submarine interconnection of power grids are seabed geological formations between two tie points (St. Croix for example), the potential to become too reliant on neighboring bodies to meet local electrical demand, and the high costs associated with the installation of submarine cabling itself.

The one section of cable between mainland Puerto Rico and St. Thomas was estimated to cost $120M for a high voltage alternating current (HVAC) line, and $176M for a high voltage direct current (HVDC) line[120]. The countries could share the cost and approach Development Banks (with appetite for electrical projects and renewable energy) for funding, such as the Inter-American Development Bank, Caribbean Development Bank, International Monetary Fund, or International Finance Corporation (World Bank) just to name a few. With renewable energy projects and power grid upgrades mostly proven to yield solid returns, as well as helping fight climate change, many institutions have chosen to finance these projects as part of their long-term investment strategies. A noteworthy option for reducing the costs associated with a Puerto Rico – USVI interconnection is to explore the path from Vieques and/or Culebra to St. Thomas or St. John, a path that has been lacking attention and analysis over the years. These paths would reduce the overall length of cable needed, dramatically reducing the expense of the project since the actual cables represent more than *80%* of the total costs of the project[121]. Building utility-scale renewable energy projects on Culebra and/or Vieques would make these islands more attractive as viable options for interconnection points since they would have large sources of generation, making them better able to supply power demands of small neighboring islands such as the USVI. Developing greater pockets of distributed generation with renewable energy from Independent Power Producers (IPP) would also support a transition towards more competitive wholesale markets.

[119] Arizu, Beatriz, et al. "Regulating Transmission: Why System Operators Must Be Truly Independent." *The World Bank Group: Private Sector and Infrastructure Network*, no. 226, January 2001. *Public Policy for the Private Sector*.
[120] "Synergy and Interconnection Projects." *Puerto Rico Electric Power Authority and InterAmerican Energy Sources*, 7 April 2011, p. 8
[121] "Interconnection Feasibility Study - Final Report." *Siemens: Prepared for Virgin Islands Water & Power Authority*, 1 August 2011, pp. 9-3 – 9-5

Deregulation and Wholesale Energy Markets

Additional advancements could occur in Puerto Rico's power sector through means of changes to the economic models or financial structures by which PREPA operates. Currently, this electric utility is publicly owned and largely vertically integrated; there is very little competition present in Puerto Rico's power industry. The consequences of lack of private enterprise and competition are well documented and typically result in a product or service that is of lower quality, less efficient, and more expensive when compared to the same goods produced through private business and we can certainly see this with the electricity produced and consumed in Puerto Rico. PREPA recently made the decision to privatize the operation and maintenance (O+M) of the island's T&D network and ultimately awarded a contract for these services to newly formed company LUMA Energy[122]. The next step would be to liberalize the buying and selling of electricity with the introduction of wholesale markets and implementation of locational marginal pricing (LMP) to reduce the overall cost of electricity. We also saw a major shift in energy markets in the U.S. during the process of deregulation which separated the generation and T&D businesses of energy companies, generally leading to more competitive prices for the average consumer[123].

Conclusion

The increase in privately constructed renewable energy plants would influence the local markets by introducing more competitive supplies of electricity, while simultaneously strengthening the area's electric reliability through decentralizing the power supply. The impact that a large utility-scale solar farm on Culebra may have on the regional energy landscape should not be underestimated or overlooked. All of these potential ancillary effects – *Vieques renewable energy*, *offshore wind*, *regional interconnections*, and a *privatized power industry* – share symbiotic relationships and can each influence the other. If an analysis of contemporary challenges endured by PREPA and the power grid in Puerto Rico has taught us anything, it is that real fundamental change is needed. An energy transition toward smaller decentralized supplies with microgrid applications are needed to resolve the inadequacies and vulnerability of the current configuration. This is especially true for the island municipalities of Vieques and Culebra, who

[122] "Puerto Rico Public-Private Partnership for the Electric Power Transmission and Distribution System." *Puerto Rico Public-Private Partnership Committee Report*, May 2020, p. 3-6

[123] Warwick, W. M. "A Primer on Electric Utilities, Deregulation, and Restructuring of U.S. Electricity Markets (Rev. 2)." *Pacific Northwest National Laboratory: Prepared for the U.S. Department of Energy*, May 2002, pp. 7.1-7.3

stand to gain the most from more resilient and flexible energy infrastructure, to better handle PREPA’s mismanagement as well as extreme weather events during an era of climate change. Let the first domino fall in Culebra, with the installation of a utility-scale solar farm.

APPENDICES

APPENDIX A (Site 1 – Barrio Frailes)

HelioScope — Annual Production Report produced by Federico Sotomayor

Frailes Culebra - Frailes, Culebra

Report

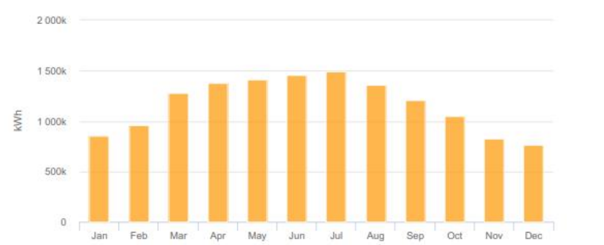
Project Name	Culebra - Frailes
Project Address	Culebra
Prepared By	Federico Sotomayor fsotomayor@clarku.edu

System Metrics

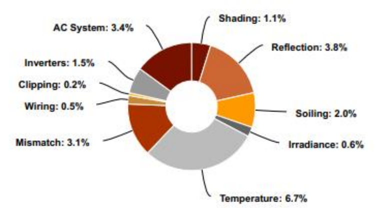
Design	Frailes
Module DC Nameplate	10.1 MW
Inverter AC Nameplate	8.10 MW Load Ratio: 1.24
Annual Production	14.04 GWh
Performance Ratio	79.2%
kWh/kWp	1,392.7
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Simulator Version	e7cafe1847-af844df5cc-543b4be639-48d0a8924b

Project Location

Monthly Production



Sources of System Loss



Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,899.1	
	POA Irradiance	1,757.9	-7.4%
	Shaded Irradiance	1,738.6	-1.1%
	Irradiance after Reflection	1,672.4	-3.8%
	Irradiance after Soiling	1,638.9	-2.0%
	Total Collector Irradiance	**1,638.9**	**0.0%**
Energy (kWh)	Nameplate	16,518,222.6	
	Output at Irradiance Levels	16,426,667.7	-0.6%
	Output at Cell Temperature Derate	15,325,199.5	-6.7%
	Output After Mismatch	14,851,768.2	-3.1%
	Optimal DC Output	14,778,832.0	-0.5%
	Constrained DC Output	14,755,750.8	-0.2%
	Inverter Output	14,534,341.7	-1.5%
	Energy to Grid	**14,038,555.1**	**-3.4%**
Temperature Metrics			
	Avg. Operating Ambient Temp		27.8 °C
	Avg. Operating Cell Temp		36.5 °C
Simulation Metrics			
	Operating Hours		4555
	Solved Hours		4555

Condition Set

Description	Condition Set 1
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model
Irradiation Variance	5%
Cell Temperature Spread	4° C
Module Binning Range	-2.5% to 2.5%
AC System Derate	0.50%

Temperature Model Parameters

Rack Type	a	b	Temperature Delta
Fixed Tilt	-3.56	-0.075	3°C
Flush Mount	-2.81	-0.0455	0°C

Soiling (%)

J	F	M	A	M	J	J	A	S	O	N	D
2	2	2	2	2	2	2	2	2	2	2	2

Module Characterizations

Module	Uploaded By	Characterization
TSM-DEG14(II) 350W (Trina Solar)	Folsom Labs	Spec Sheet Characterization, PAN

Component Characterizations

Device	Uploaded By	Characterization
Trinergy Plus-50kW (400V) (AEC)	Folsom Labs	Spec Sheet

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Figure 4.1 – HelioScope Report Production Modeling Simulation Results Site 1 Frailes (p.1)

HelioScope

Annual Production Report produced by Federico Sotomayor

Components

Component	Name	Count
Inverters	Trinergy Plus-50kW (400V) (AEC)	162 (8.10 MW)
AC Home Runs	1/0 AWG (Aluminum)	162 (433,163.0 ft)
Home Runs	12 AWG (Copper)	162 (491.8 ft)
Combiners	11 input Combiner	144
Combiners	12 input Combiner	18
Strings	10 AWG (Copper)	1,800 (655,102.9 ft)
Module	Trina Solar, TSM-DEG14(II) 350W (350W)	28,800 (10.1 MW)

Wiring Zones

Description	Combiner Poles	String Size	Stringing Strategy
Wiring Zone	12	16-16	Along Racking

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
Field Segment 1	Fixed Tilt	Landscape (Horizontal)	15°	360°	10.0 ft	4x20	360	28,800	10.1 MW

Detailed Layout

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Figure 4.2 – HelioScope Report Production Modeling Simulation Results Site 1 Frailes (p.2)

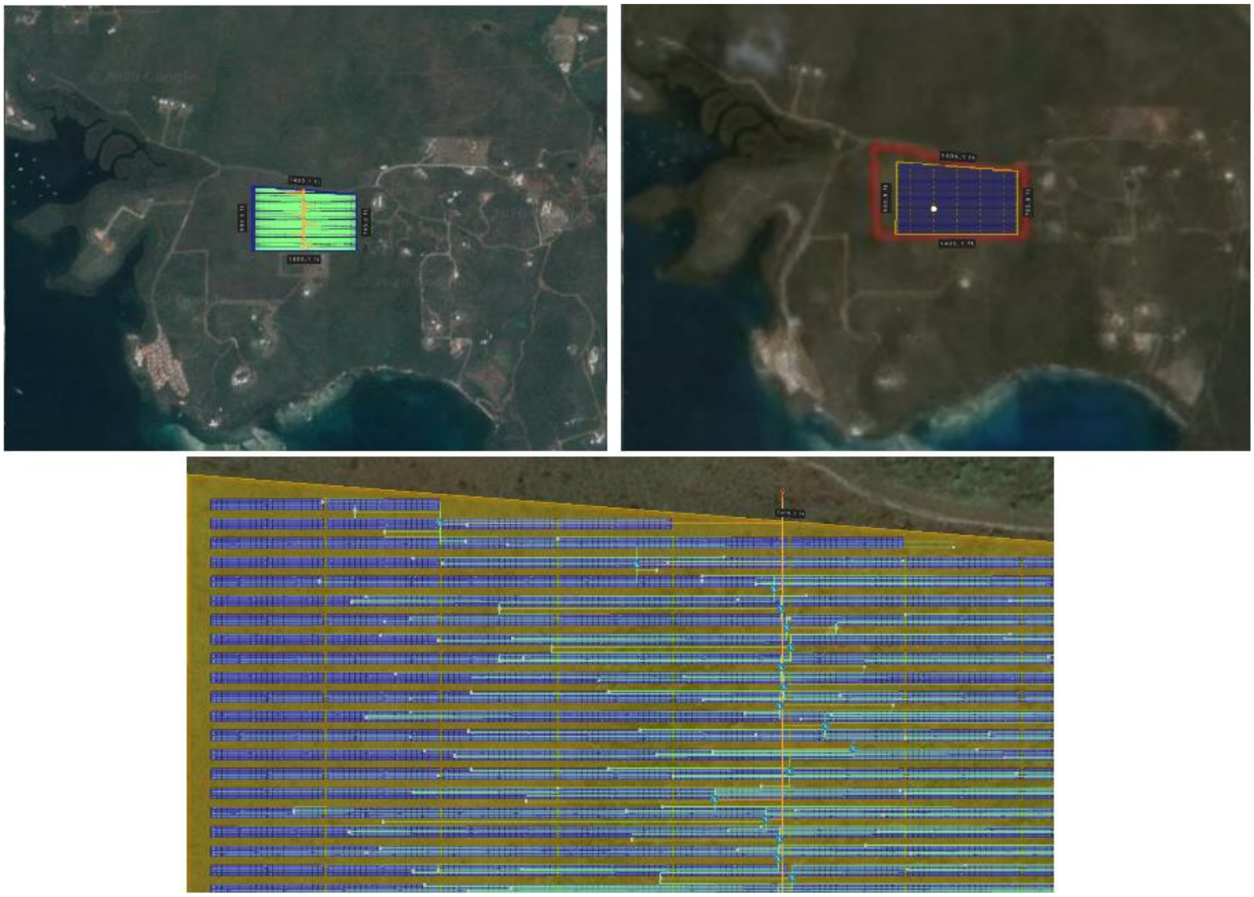
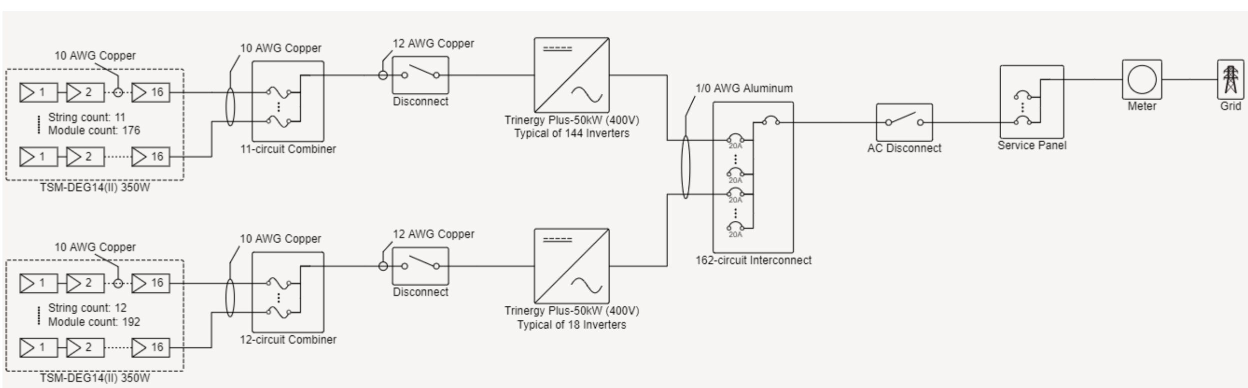


Figure 4.3 – HelioScope Bird's Eye View Solar Farm Site 1 Frailes at Various Heights



Module Specifications	
28800x Trina Solar TSM-DEG14(II) 350W	
STC Rating	350 W
Vmp	38.5 V
Imp	9.09 A
Voc	46.9 V
Isc	9.6 A

Inverter Specifications	
162x AEC Trinergy Plus-50kW (400V)	
Max AC Power Rating	50 kW
Max Input Voltage	1,000 V
Min AC Power Rating	0 W
Min Input Voltage	570 V

Wire Schedule		
Tier	Wire	Length
AC Branch	162x 1/0 AWG	433163ft
Bus	162x 12 AWG	492ft
String	1800x 10 AWG	655103ft

Figure 4.4 – HelioScope Single Line Diagram for Solar Farm Site 1 Frailes

Caution: Photovoltaic system performance predictions calculated by PVWatts® include many inherent assumptions and uncertainties and do not reflect variations between PV technologies nor site-specific characteristics except as represented by PVWatts® inputs. For example, PV modules with better performance are not differentiated within PVWatts® from lesser performing modules. Both NREL and private companies provide more sophisticated PV modeling tools (such as the System Advisor Model at https://sam.nrel.gov) that allow for more precise and complex modeling of PV systems.

The expected range is based on 30 years of actual weather data at the given location and is intended to provide an indication of the variation you might see. For more information, please refer to this NREL report: The Error Report.

The energy output range is based on analysis of 30 years of historical weather data for nearby , and is intended to provide an indication of the possible interannual variability in generation for a Fixed (open rack) PV system at this location.

RESULTS

13,693,421 kWh/Year*

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	3.70	813,317	89,465
February	4.60	914,076	100,548
March	5.53	1,245,059	136,956
April	6.24	1,349,924	148,492
May	6.37	1,421,240	156,336
June	6.62	1,436,638	158,030
July	6.54	1,468,808	161,569
August	6.21	1,383,226	152,155
September	5.43	1,161,015	127,712
October	4.66	1,024,678	112,715
November	3.63	761,495	83,764
December	3.31	713,949	78,534
Annual	**5.24**	**13,693,425**	**$ 1,506,276**

Location and Station Identification

Requested Location	culebra, puerto rico
Weather Data Source	Lat, Lon: 18.29, -65.3 0.9 mi
Latitude	18.29° N
Longitude	65.3° W

PV System Specifications *(Commercial)*

DC System Size	10080.0 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	15°
Array Azimuth	359°
System Losses	20%
Inverter Efficiency	98%
DC to AC Size Ratio	1.24

Economics

Average Retail Electricity Rate	0.110 $/kWh

Performance Metrics

Capacity Factor	15.5%

Figure 4.5 – PVWatts Report Production Modeling Simulation Results Site 1 Frailes (p.1)

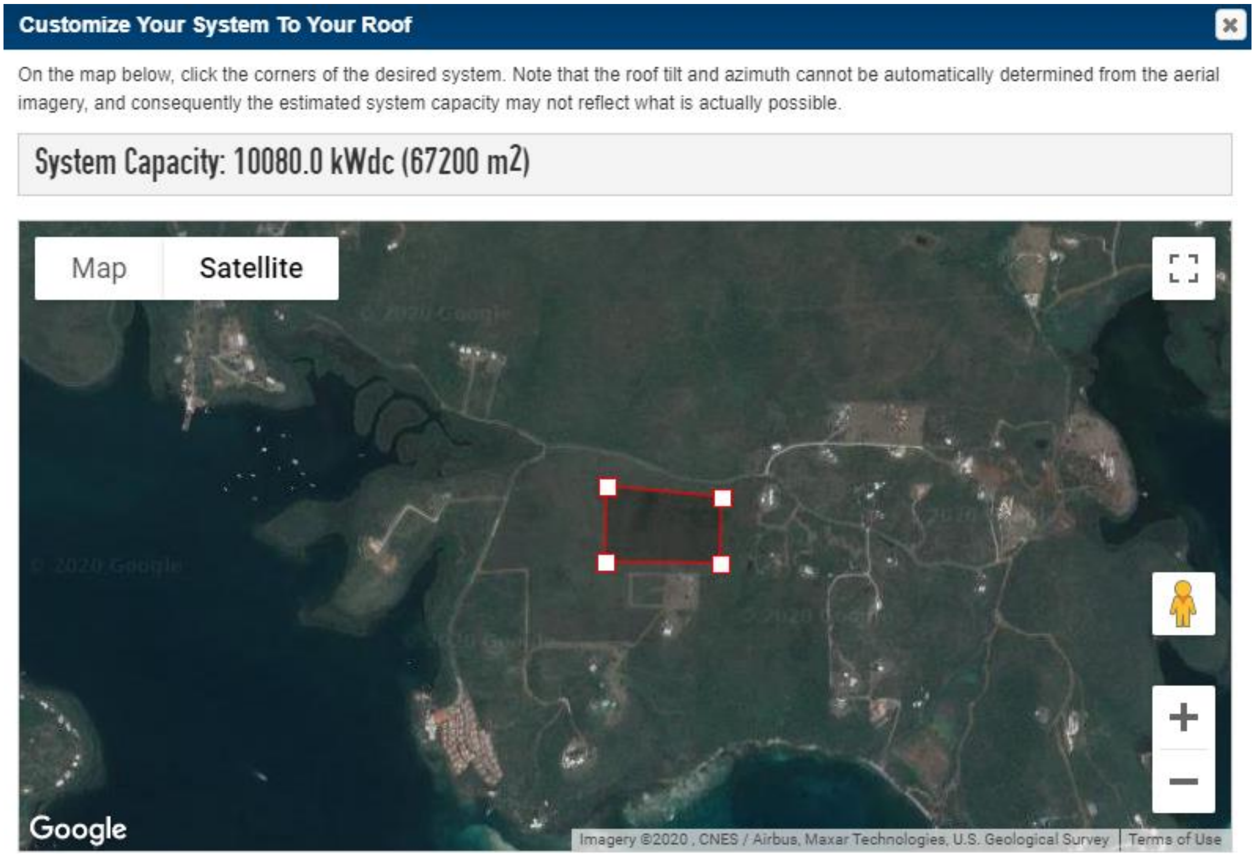


Figure 4.6 – PVWatts Report Production Modeling Simulation Results Site 1 Frailes (p.2)

APPENDIX B (Site 2 – Barrio San Isidro)

HelioScope — Annual Production Report produced by Federico Sotomayor

San Isidro Culebra - San Isidro, Culebra

Report

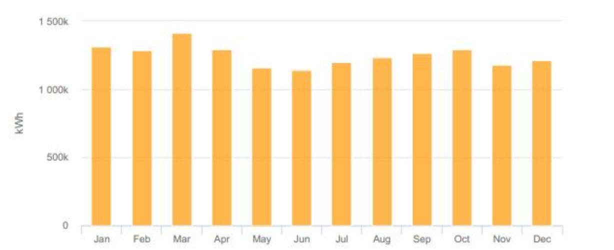
Project Name	Culebra - San Isidro
Project Address	Culebra
Prepared By	Federico Sotomayor fsotomayor@clarku.edu

System Metrics

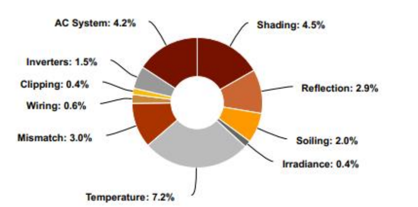
Design	San Isidro
Module DC Nameplate	10.1 MW
Inverter AC Nameplate	8.10 MW Load Ratio: 1.24
Annual Production	14.98 GWh
Performance Ratio	76.0%
kWh/kWp	1,486.5
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Simulator Version	e7cafe1847-af844df5cc-543b4be639-48d0a8924b

Project Location

Monthly Production



Sources of System Loss



Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,899.1	
	POA Irradiance	1,954.7	2.9%
	Shaded Irradiance	1,867.1	-4.5%
	Irradiance after Reflection	1,812.5	-2.9%
	Irradiance after Soiling	1,776.3	-2.0%
	Total Collector Irradiance	**1,776.1**	**0.0%**
Energy (kWh)	Nameplate	17,901,213.6	
	Output at Irradiance Levels	17,821,322.3	-0.4%
	Output at Cell Temperature Derate	16,539,960.9	-7.2%
	Output After Mismatch	16,045,287.8	-3.0%
	Optimal DC Output	15,949,992.6	-0.6%
	Constrained DC Output	15,884,577.9	-0.4%
	Inverter Output	15,645,800.0	-1.5%
	Energy to Grid	**14,984,300.0**	**-4.2%**
Temperature Metrics			
	Avg. Operating Ambient Temp		27.8 °C
	Avg. Operating Cell Temp		37.2 °C
Simulation Metrics			
		Operating Hours	4555
		Solved Hours	4555

Condition Set

Description	Condition Set 1
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model
Irradiation Variance	5%
Cell Temperature Spread	4° C
Module Binning Range	-2.5% to 2.5%
AC System Derate	0.50%

Temperature Model Parameters

Rack Type	a	b	Temperature Delta
Fixed Tilt	-3.56	-0.075	3°C
Flush Mount	-2.81	-0.0455	0°C

Soiling (%)

J	F	M	A	M	J	J	A	S	O	N	D
2	2	2	2	2	2	2	2	2	2	2	2

Module Characterizations

Module	Uploaded By	Characterization
TSM-DEG14(II) 350W (Trina Solar)	Folsom Labs	Spec Sheet Characterization, PAN

Component Characterizations

Device	Uploaded By	Characterization
Trinergy Plus-50kW (400V) (AEC)	Folsom Labs	Spec Sheet

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Figure 5.1 – HelioScope Report Production Modeling Simulation Results Site 2 San Isidro (p.1)

HelioScope — Annual Production Report produced by Federico Sotomayor

Components

Component	Name	Count
Inverters	Trinergy Plus-50kW (400V) (AEC)	162 (8.10 MW)
AC Home Runs	1/0 AWG (Aluminum)	162 (494,375.2 ft)
Home Runs	12 AWG (Copper)	162 (662.1 ft)
Home Runs	10 AWG (Copper)	162 (1,247.0 ft)
Combiners	1 input Combiner	162
Combiners	11 input Combiner	144
Combiners	12 input Combiner	18
Strings	10 AWG (Copper)	1,800 (571,261.6 ft)
Module	Trina Solar, TSM-DEG14(II) 350W (350W)	28,800 (10.1 MW)

Wiring Zones

Description	Combiner Poles	String Size	Stringing Strategy
Wiring Zone	12	16-16	Along Racking

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
San Isidro	Fixed Tilt	Landscape (Horizontal)	30°	190°	10.0 ft	4x20	360	28,800	10.1 MW

Detailed Layout

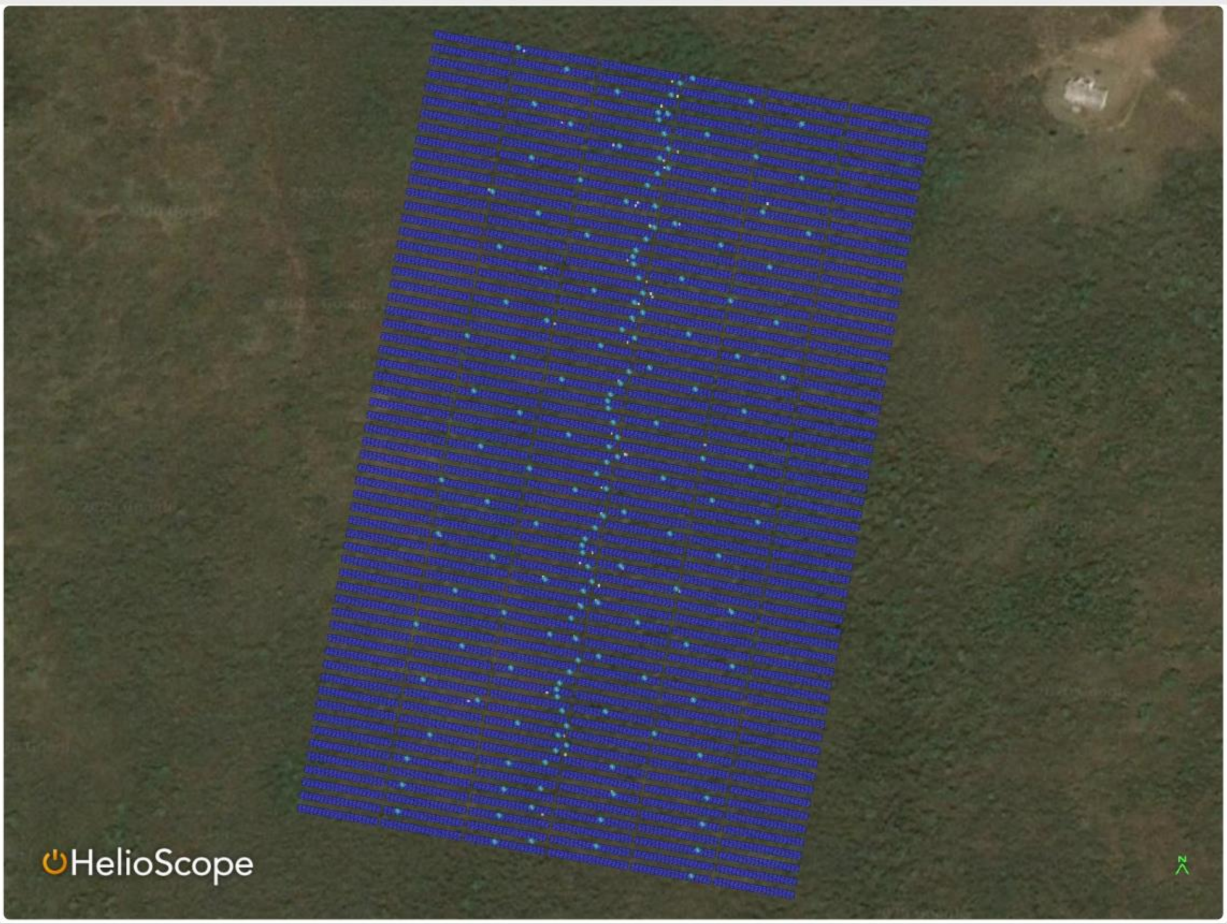

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Figure 5.2 – HelioScope Report Production Modeling Simulation Results Site 2 San Isidro (p.2)

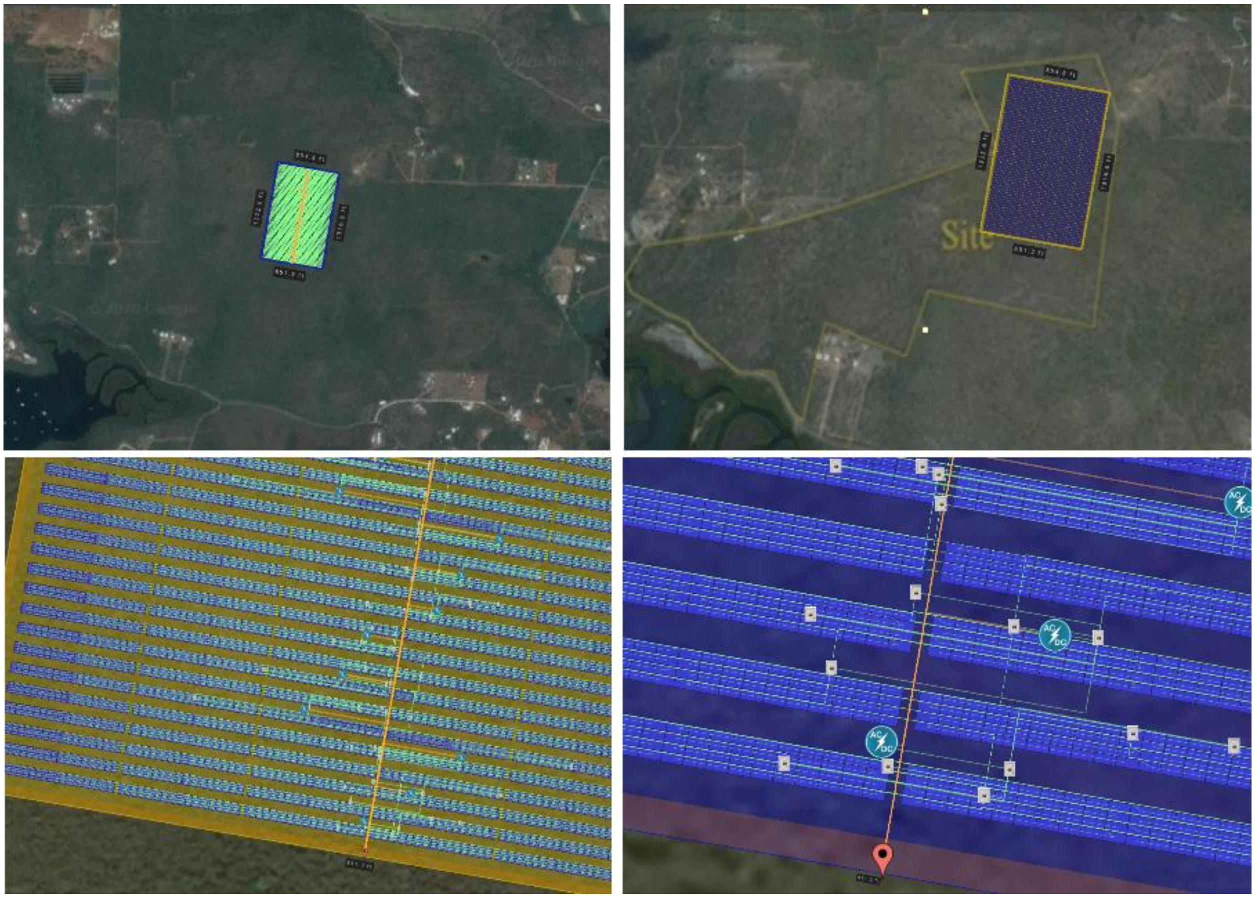
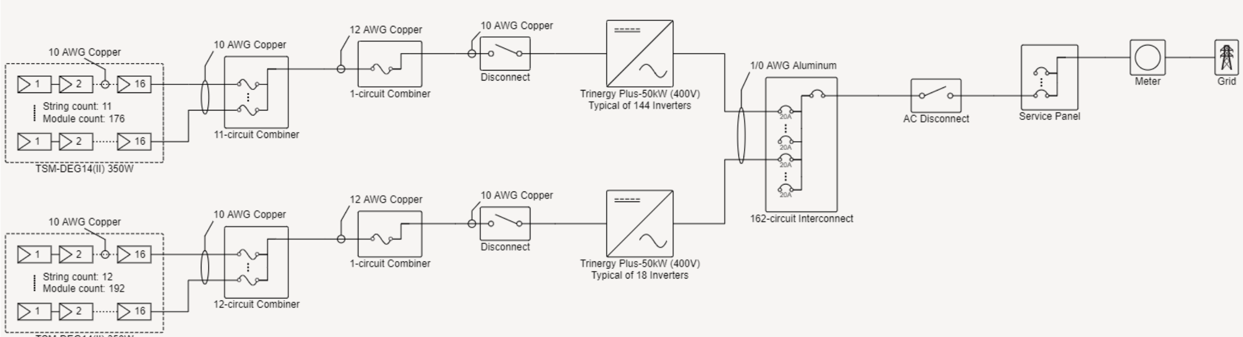


Figure 5.3 – HelioScope Bird's Eye View Solar Farm Site 2 San Isidro at Various Heights



Module Specifications	
28800x Trina Solar TSM-DEG14(II) 350W	
STC Rating	350 W
Vmp	38.5 V
Imp	9.09 A
Voc	46.9 V
Isc	9.6 A

Inverter Specifications	
162x AEC Trinergy Plus-50kW (400V)	
Max AC Power Rating	50 kW
Max Input Voltage	1,000 V
Min AC Power Rating	0 W
Min Input Voltage	570 V

Wire Schedule		
Tier	Wire	Length
AC Branch	162x 1/0 AWG	494375ft
Trunk	162x 10 AWG	918ft
Bus	162x 12 AWG	662ft
String	1800x 10 AWG	572036ft

Figure 5.4 – HelioScope Single Line Diagram for Solar Farm Site 2 San Isidro

NREL

NATIONAL RENEWABLE ENERGY LABORATORY

Caution: Photovoltaic system performance predictions calculated by PVWatts® include many inherent assumptions and uncertainties and do not reflect variations between PV technologies nor site-specific characteristics except as represented by PVWatts® inputs. For example, PV modules with better performance are not differentiated within PVWatts® from lesser performing modules. Both NREL and private companies provide more sophisticated PV modeling tools (such as the System Advisor Model at https://sam.nrel.gov) that allow for more precise and complex modeling of PV systems.

The expected range is based on 30 years of actual weather data at the given location and is intended to provide an indication of the variation you might see. For more information, please refer to this NREL report: The Error Report.

The energy output range is based on analysis of 30 years of historical weather data for nearby , and is intended to provide an indication of the possible interannual variability in generation for a Fixed (open rack) PV system at this location.

RESULTS

14,790,004 kWh/Year*

Month	Solar Radiation (kWh / m² / day)	AC Energy (kWh)	Value ($)
January	6.35	1,351,430	148,657
February	6.67	1,268,830	139,571
March	6.52	1,395,315	153,485
April	6.03	1,235,780	135,936
May	5.40	1,141,496	125,565
June	5.33	1,095,939	120,553
July	5.42	1,152,152	126,737
August	5.73	1,208,202	132,902
September	5.93	1,201,268	132,139
October	6.17	1,290,104	141,911
November	5.81	1,178,429	129,627
December	6.01	1,271,059	139,816
Annual	**5.95**	**14,790,004**	**$ 1,626,899**

Location and Station Identification

Requested Location	culebra, puerto rico
Weather Data Source	Lat, Lon: 18.29, -65.3 0.9 mi
Latitude	18.29° N
Longitude	65.3° W

PV System Specifications *(Commercial)*

DC System Size	10088.3 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	30°
Array Azimuth	190°
System Losses	24%
Inverter Efficiency	98%
DC to AC Size Ratio	1.24

Economics

Average Retail Electricity Rate	0.110 $/kWh

Performance Metrics

Capacity Factor	16.7%

Figure 5.5 – PVWatts Report Production Modeling Simulation Results Site 2 San Isidro (p.1)

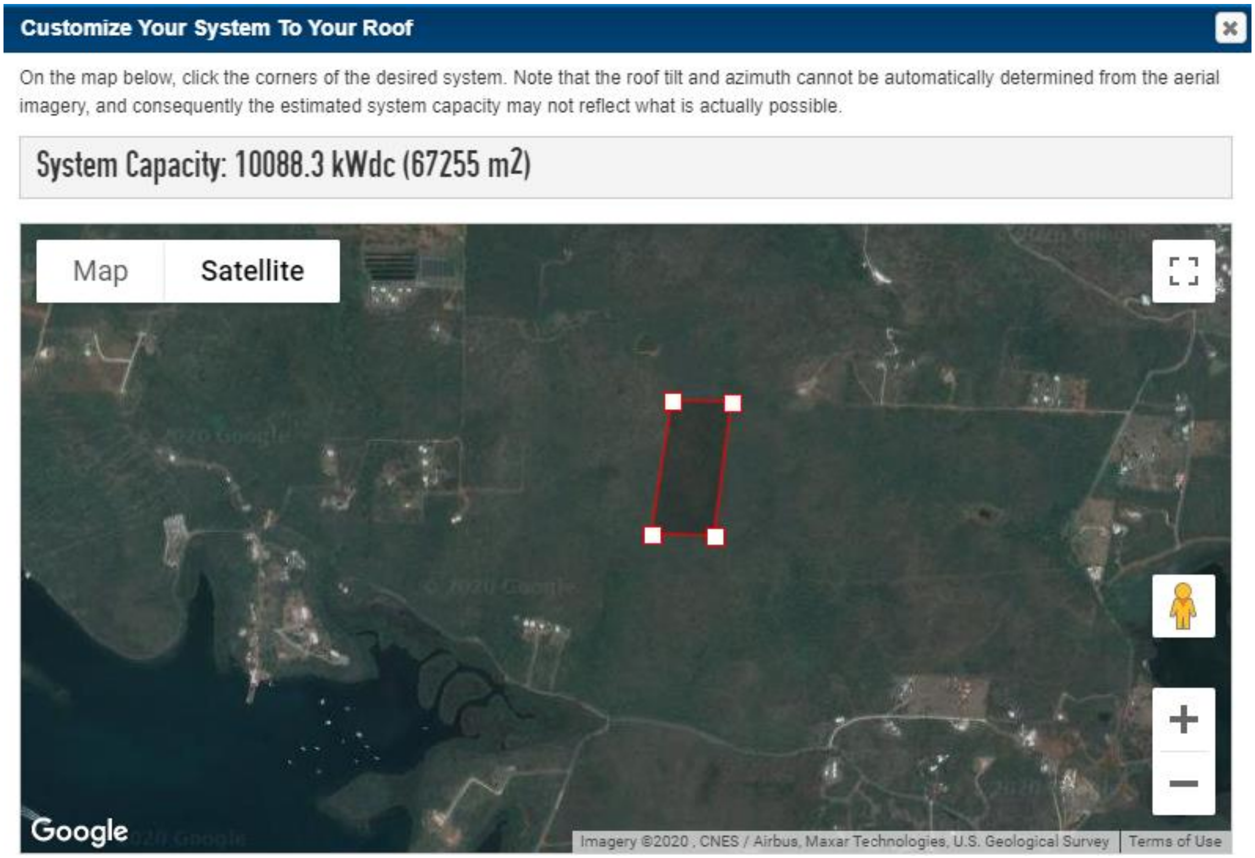


Figure 5.6 – PVWatts Report Production Modeling Simulation Results Site 2 San Isidro (p.2)

APPENDIX C (Site 3 – Barrio Playa Sardinas)

HelioScope — Annual Production Report produced by Federico Sotomayor

Playa Sardinas Culebra - Playa Sardinas, Culebra

Report

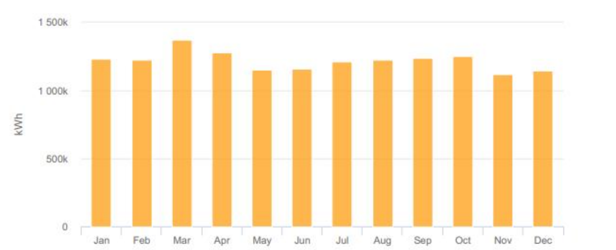
Project Name	Culebra - Playa Sardinas
Project Address	Culebra
Prepared By	Federico Sotomayor fsotomayor@clarku.edu

System Metrics

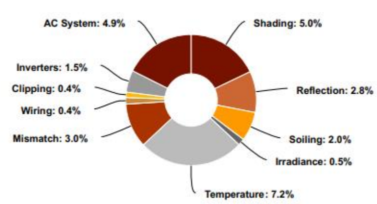
Design	Playa Sardinas
Module DC Nameplate	10.1 MW
Inverter AC Nameplate	8.10 MW Load Ratio: 1.24
Annual Production	14.62 GWh
Performance Ratio	75.3%
kWh/kWp	1,450.5
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Simulator Version	e7cafe1847-af844df5cc-543b4be639-48d0a8924b

Project Location

Monthly Production



Sources of System Loss



Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,899.1	
	POA Irradiance	1,927.6	1.5%
	Shaded Irradiance	1,831.8	-5.0%
	Irradiance after Reflection	1,780.1	-2.8%
	Irradiance after Soiling	1,744.5	-2.0%
	Total Collector Irradiance	**1,744.2**	**0.0%**
Energy (kWh)	Nameplate	17,579,927.3	
	Output at Irradiance Levels	17,498,388.0	-0.5%
	Output at Cell Temperature Derate	16,230,541.2	-7.2%
	Output After Mismatch	15,736,426.2	-3.0%
	Optimal DC Output	15,665,940.0	-0.4%
	Constrained DC Output	15,607,712.6	-0.4%
	Inverter Output	15,373,200.0	-1.5%
	Energy to Grid	**14,621,100.0**	**-4.9%**
Temperature Metrics			
	Avg. Operating Ambient Temp		27.8 °C
	Avg. Operating Cell Temp		37.0 °C
Simulation Metrics			
		Operating Hours	4555
		Solved Hours	4555

Condition Set

Description	Condition Set 1
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model
Irradiation Variance	5%
Cell Temperature Spread	4° C
Module Binning Range	-2.5% to 2.5%
AC System Derate	0.50%

Temperature Model Parameters

Rack Type	a	b	Temperature Delta
Fixed Tilt	-3.56	-0.075	3°C
Flush Mount	-2.81	-0.0455	0°C

Soiling (%)

J	F	M	A	M	J	J	A	S	O	N	D
2	2	2	2	2	2	2	2	2	2	2	2

Module Characterizations

Module	Uploaded By	Characterization
TSM-DEG14(II) 350W (Trina Solar)	Folsom Labs	Spec Sheet Characterization, PAN

Component Characterizations

Device	Uploaded By	Characterization
Trinergy Plus-50kW (400V) (AEC)	Folsom Labs	Spec Sheet

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Figure 6.1 – HelioScope Report Production Modeling Simulation Results Site 3 Playa Sardinas (p.1)

HelioScope

Annual Production Report produced by Federico Sotomayor

Components

Component	Name	Count
Inverters	Trinergy Plus-50kW (400V) (AEC)	162 (8.10 MW)
AC Home Runs	1/0 AWG (Aluminum)	162 (553,118.2 ft)
Home Runs	12 AWG (Copper)	162 (46.2 ft)
Combiners	11 input Combiner	144
Combiners	12 input Combiner	18
Strings	10 AWG (Copper)	1,800 (542,857.4 ft)
Module	Trina Solar, TSM-DEG14(II) 350W (350W)	28,800 (10.1 MW)

Wiring Zones

Description	Combiner Poles	String Size	Stringing Strategy
Wiring Zone	12	16-16	Along Racking

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
Field Segment 1	Fixed Tilt	Landscape (Horizontal)	30°	210°	10.0 ft	4x20	360	28,800	10.1 MW

Detailed Layout

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Figure 6.2 – HelioScope Report Production Modeling Simulation Results Site 3 Playa Sardinas (p.2)

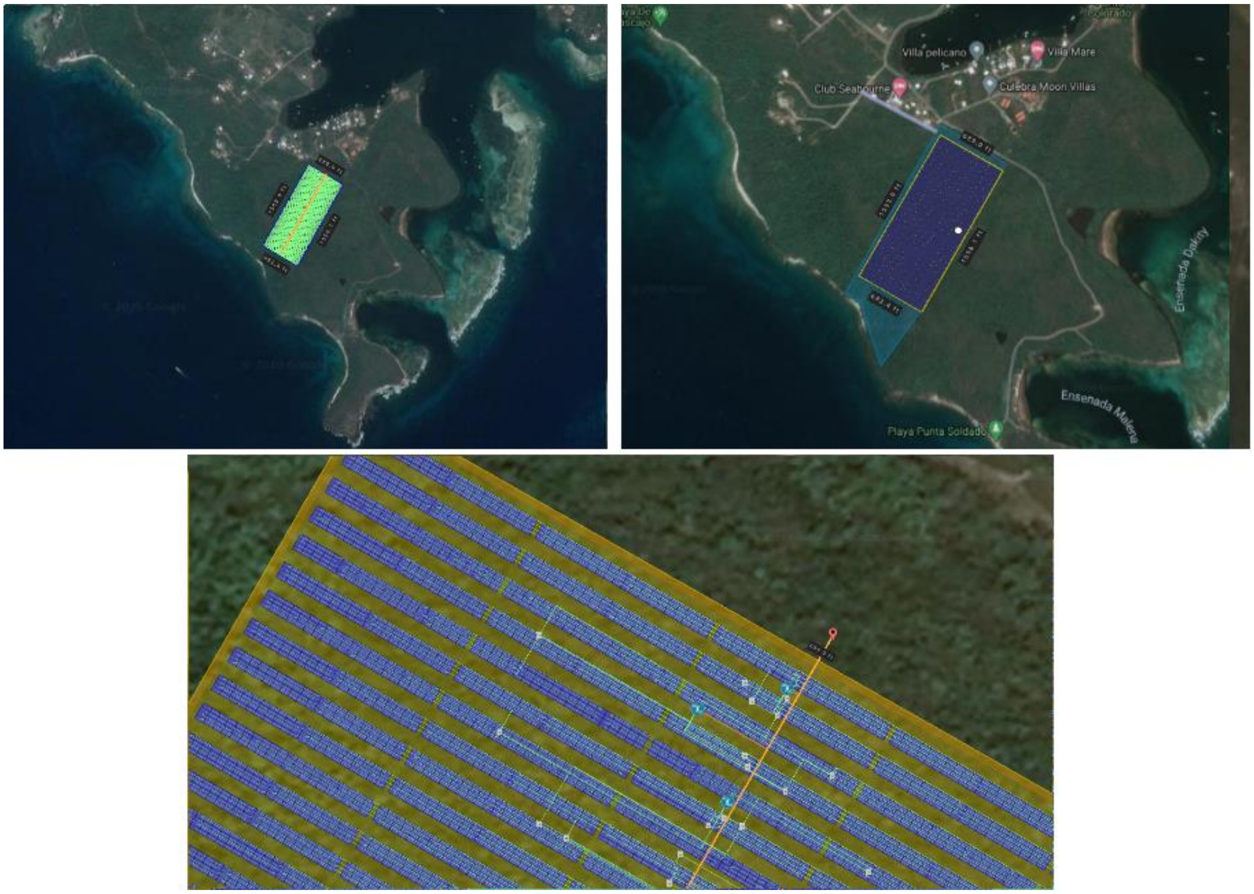
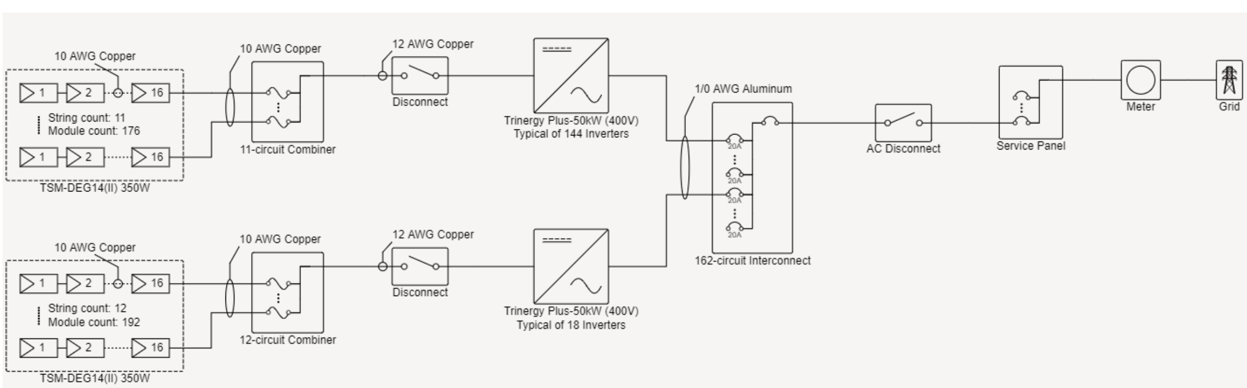


Figure 6.3 – HelioScope Bird's Eye View Solar Farm Site 3 Playa Sardinas at Various Heights



Module Specifications	
28800x Trina Solar TSM-DEG14(II) 350W	
STC Rating	350 W
Vmp	38.5 V
Imp	9.09 A
Voc	46.9 V
Isc	9.6 A

Inverter Specifications	
162x AEC Trinergy Plus-50kW (400V)	
Max AC Power Rating	50 kW
Max Input Voltage	1,000 V
Min AC Power Rating	0 W
Min Input Voltage	570 V

Wire Schedule		
Tier	Wire	Length
AC Branch	162x 1/0 AWG	553118ft
Bus	162x 12 AWG	46ft
String	1800x 10 AWG	542857ft

Figure 6.4 – HelioScope Single Line Diagram for Solar Farm Site 3 Playa Sardinas

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The energy output range is based on analysis of 30 years of historical weather data for nearby , and is intended to provide an indication of the possible interannual variability in generation for a Fixed (open rack) PV system at this location.

RESULTS

14,528,560 kWh/Year*

Month	Solar Radiation (kWh / m² / day)	AC Energy (kWh)	Value ($)
January	6.16	1,304,586	143,504
February	6.43	1,218,704	134,057
March	6.43	1,372,877	151,016
April	6.06	1,238,009	136,181
May	5.48	1,156,988	127,269
June	5.40	1,107,465	121,821
July	5.49	1,164,927	128,142
August	5.72	1,204,110	132,452
September	5.85	1,179,200	129,712
October	6.01	1,249,882	137,487
November	5.55	1,118,460	123,031
December	5.77	1,213,354	133,469
Annual	**5.86**	**14,528,562**	**$ 1,598,141**

Location and Station Identification

Requested Location	culebra, puerto rico
Weather Data Source	Lat, Lon: 18.29, -65.3 0.9 mi
Latitude	18.29° N
Longitude	65.3° W

PV System Specifications *(Commercial)*

DC System Size	10085.4 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	30°
Array Azimuth	210°
System Losses	24.25%
Inverter Efficiency	98%
DC to AC Size Ratio	1.24

Economics

Average Retail Electricity Rate	0.110 $/kWh

Performance Metrics

Capacity Factor	16.4%

Figure 6.5 – PVWatts Report Production Modeling Simulation Results Site 3 Playa Sardinas (p.1)

Figure 6.6 – PVWatts Report Production Modeling Simulation Results Site 3 Playa Sardinas (p.2)

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