PUERTO RICO POWER SYSTEM TRANSITION TO RENEWABLE ENERGY

by

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Dedication

I dedicate this research project to the resilient citizens on the Island of Puerto Rico who have faced catastrophic events, governmental instability, and pandemic situations. Still, the contagious festive spirit lets them continue fighting for a change.

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List of Abbreviations

AAFAF	Puerto Rico Fiscal Agency and Financial Advisory Authority
AC	Analog Current
AES	Applied Energy Services
CO_2	Carbon Dioxide
DC	Direct Current
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FOMB	Financial Oversight and Management Board for Puerto Rico
ITC	Investment Tax Credit
kWh	kilo Watt-hour
LEED	Leadership in Energy and Environmental Design
mkWh	million-kilo Watt-hour
NAE	National Academy of Engineering
NREL	National Renewable Energy Laboratory
P3A	Puerto Rico Public-Private Partnership Authority
PREPA	Puerto Rico Electric and Power Authority
PROMESA	Puerto Rico Oversight, Management, and Economic Stability Act
PV	Photovoltaic
RSA	Restructuring Support Agreement
T&D	Transmission and Distribution

Glossary

Solar Photovoltaic: An electrical system consisting of a PV module array and other supporting systems to convert solar energy to electricity**.**

Net Metering: Customers receives a monthly credit from the energy produced by their system.

Abstract

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Puerto Rico's lack of effective and affordable energy substitutes after Hurricane Maria resulted in a mortality increase of 4,970 residents (Verma, Murray, and Mamdani, 2018). Puerto Rico's Island dependency on electric power and no energy substitutes available have provoked a risk to human life after catastrophic events. The problem was measured by comparing Puerto Rico's reliance on fossil fuels with accessible and economical renewable energy options. Solar photovoltaic (PV) technologies are the optimum alternative to transition from fossil fuel usage to renewable energy. Previous research has demonstrated the impact of using solar panels instead of an electric grid due to the constant solar radiation throughout the year. The analyzed data and projections showed a reduction in fossil fuels and carbon dioxide emissions by implementing solar photovoltaic technologies. The installation of PV systems in landfills, household roofs and transitioning to solar public lighting positively impacts the atmosphere carbon dioxide emissions.

CHAPTER 1. INTRODUCTION

1.1 Puerto Rico's Catastrophic Energy Situation

The Puerto Rico Energy Public Policy Act, S.B. 1121, signed on April 11, 2019, converted into law the transition of Puerto Rico's power system to 100% renewable energy sources by 2050 (*Act No. 17-2019 S. B. 1121*, 2019). The act establishes a public policy to promote a resilient energy generation and distribution system with reasonable costs to residential, commercial, and industrial users (Act No. 17-2019 S. B. 1121, 2019). Hurricane Irma and Maria hit the Island of Puerto Rico two weeks apart on September 2017 causing harmful effects to most of the essential services on the Island (Gallucci, 2018). The electric power system of Puerto Rico collapsed and no renewable energy substitutes and material supplies were available to mitigate rapidly in restoring the system (Gallucci, 2018). The transmission lines failed after the hurricane passed by "toppling transmission towers, snapping concrete power poles, entangling lines, and battering power plants" (Gallucci, 2018, p.1) leaving the entire Island in a total blackout.

1.2 Puerto Rico's Dependence on One Energy Source

Puerto Rico's lack of effective and affordable energy substitutes after Hurricane Maria resulted in a mortality increase of 4,970 residents (Mamdani, Murray and Verma, 2018). Several families used power generators to maintain foods refrigerated but the lack of access to gasoline, natural gas, and diesel added a burden to the precarious situation. On January 6, 2020 a magnitude 6.4 earthquake shook the entire Island with an epicenter located at the South part of Puerto Rico (McArdle, 2020). The Costa Sur Power plant, located near the epicenter, control center crash leaving Puerto Rico once again without power (McArdle, 2020). The earthquake aftermath resulted in damages to the energy generation system instead of transmission lines that were destroyed during Hurricane Maria.

The Puerto Rico Electric and Power Authority (PREPA), a government-owned corporation provides electric power generation, distribution, and transmission to the majority of Puerto Rico inhabitants. The U.S. Energy Information Administration reported 40% energy generation from petroleum, 39% from natural gas, 18% from coal, and 2.3% from renewables in Puerto Rico (EIA, 2019). PREPA relies on fossil fuels as the primary source of power generation on the Island (EIA, 2019). Consequences of the Hurricane Maria and earthquakes have worsened PREPA's stability and its ability to maintain and recover during catastrophic events (Act No. 17-2019 S. B. 1121, 2019). PREPA's debts to creditors, Puerto Rico recession and its inability to restructure the system forced Barack Obama administration to signed and enact Public Law 114-187. The Public Law 114-187 enacted on June 30, 2016 initiated the Puerto Rico Oversight, Management, and Economic Stability Act (PROMESA) to establish an external board that will support Puerto Rico's government to restructure the PREPA nine billion dollar ($9B) debt. The Definitive Restructuring Support Agreement (RSA) signed by the Puerto Rico Electric Power Authority ("PREPA"), Puerto Rico Fiscal Agency and Financial Advisory Authority (AAFAF), the Financial Oversight and Management Board for Puerto Rico ("FOMB"), and supporting holders establishes opposed initiatives that go against the energy public policy S.B. 1121. PROMESA priorities to resolve the debts and move to a resilient energy system do not plan changing PREPA's fossil fuels dependence to renewable energy sources.

1.3 Puerto Rico's Population in Peril due to lack of energy alternatives

A substantive lack of sufficient energy sources will cause the cost of energy in Puerto Rico to soar 64.45% by 2044 (Marxuach, 2019). The Puerto Rico Electric Power Authority (PREPA) listed the monthly general residential energy charge as $0.04944 per the first 425 kWh, $0.05564 per kWh for additional consumption, $4.00 customer charge (2019). Additional charges related to reconciliation clauses and riders will increase or decrease the energy cost. Other factors such as concession contracts to manage PREPA system can benefit or aggravate the cost of energy in the future. The Financial Oversight and Management Board (FOMB) signed an agreement on June 2020 between Puerto Rico Public-Private Partnerships Authority (P3A) and LUMA Energy Corporation to restore the electric grid system in the Puerto Rico distribution system (Alvarado, 2020). LUMA will rebuild, repair and provide preventive maintenance to the Transmission and Distribution (T&D) system (Alvarado, 2020). The signed contract will cover the customer service & billing for a 15-year period (Alvarado, 2020). LUMA expects federal funds to rebuild the system but in the absence of such fund they will be forced to impose additional charges to the cost of electricity (Alvarado, 2020). The Caribbean Business News pointed out Fermin Fontanes, P3A Executive Director, interest to incorporate and upgrade the energy systems to renewable energy as established in the Puerto Rico Energy Public Policy Act S.B. 1121. LUMA will face challenges to increase the current 2.3% from renewables to reduce dramatically the use of energy from fossil fuels (Alvarado, 2020).

1.4 How the problem is measured

The problem measured Puerto Rico's 98% reliance on fossil fuels compared to accessible and economical renewable energy options (Campbell, Clark, and Austin, 2017). The fossil fuels supplied to Puerto Rico come from imports, as the Island "has no proved reserves or production of fossil fuels" U.S. Energy Information Administration (EIA, 2019, p.1). The amount of natural gas imported to the Island was 46 billion cu. ft. by 2017 and 1,319 thousand short tons of coal by 2018 U.S. Energy Information Administration (EIA, 2020). Riders and incentives benefit customers to transition from PREPA energy dependence and invest on Solar Photovoltaic energy sources available everywhere in Puerto Rico. Even though riders and incentives exist the majority of PREPA clients do not have the credit score to borrow or the available cash amount to invest in renewable energy systems. The gap exists at the generation level to provide a robust and resilient generation and distribution system with accessible energy costs. The Net Metering Credit Rider is an agreement with PREPA where customers "receive a monthly credit from the energy produced by their system and exported into PREPA's electrical system" (PREPA, 2019).

The Solar Investment Tax Credit (ITC) is a policy mechanism that provides a 26% federal tax credit to residential, commercial, and utility solar investors advocated by the Solar Energy Industries Association (SEIA, 2020). The tax credit implementation serves as incentive for customers to reduce energy costs, improve solar industry growth, and supported business steadiness. The ITC implementation started in 2006 with 30% reduced to 26% in 2020 and will continue the reduction in 2021 up to 22% (SEIA, 2020). The long term ITC benefit will reduce to 10% for commercial and utility scale investors but will no longer exist for residential purposes in 2022 (SEIA, 2020). The Clean Energy Authority updated solar rebates and incentives for Puerto Rico but have its limitations depending on the final energy user, purpose, or business as follows:

- Building Energy Code with Mandatory Solar Water Heating (2020).
- Economic Development Incentives for Renewables (2016).
- Excise Tax Exemption for Farmers (2020).

- Green Energy Fund (2015).
- Green Energy Fund Tier I Incentive Program (2015).
- Green Energy Fund Tier II Incentive Program (2015).
- Interconnection Standards (2015).
- Net Metering (2015).
- Property Tax Exemption for Solar and Renewable Energy Equipment (2020).
- Renewable Energy Equipment Certification (2015).
- Renewable Energy Portfolio Standard (2015).
- Sales and Use Tax Exemption for Green Energy (2020).
- Solar and Wind Contractor Certification (2020).
- Tax Deduction for Solar Energy Systems (2015).

1.5 National Academy of Engineering Grand Challenge

Leveraging renewable sources of energy positively transition Puerto Rico's dependence on petroleum; subsequently, reducing carbon dioxide emissions (National Academy of Engineering, 2019). The existing electrical grid design continues contributing to carbon dioxide emissions and system malfunction or deterioration will add inefficiencies due to energy looses. Burning fossil fuels is the major contributor to Carbon Dioxide emissions to the earth's atmosphere (Holloway, 2001). The estimated yearly amount is about $22x10^9$ tonnes CO_2/year considered an alarming situation that will result in global warming (Holloway, 2001). Moving to PV technologies contributes to the reduction of CO_2 emission and other studies techniques such as CO_2 sequestration methods to reduce emissions until renewable energy options continue evolving.

Table 1.1 provides the Carbon Dioxide Emissions reported by the U.S Energy Administration Information for the period of 2017:

Table 1.1 Puerto Rico 2017 Carbon Dioxide Emissions by Source

Source	**Amount**
Total Fossil Fuels	18 million metric tons
Petroleum	14 million metric tons
Natural Gas	3 million metric tons
Coal	2 million metric tons

Dr. Osvaldo Rosario highlighted other than CO_2 harmful conditions that are hazardous by products "such as arsenic, selenium, chromium-6 and vanadium" known as toxic and suspected carcinogens" (CBS, 2020, p.1). Coal ashes are a toxic byproduct of burning coal to generate electricity. Puerto Rico has a burning coal power plant that "generates 300,000 tons of coal ash per year" (CBS, 2020, p.1). Puerto Rico laws do not permit ashes storages for more than 180 days due to its harmful effect that go against safeguarding and protecting public health and "multiple studies have shown the risk" (CBS, 2020, p.1). Storage ashes location is near a residential area in Guayama where its citizens have protested and proof of health issues such as "respiratory problems, higher levels of cancer and skin rashes" (CBS, 2020, p.1) as a result of being in contact with the toxic by product.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Puerto Rico Sunlight Description

Puerto Rico is an Island where the mean temperatures do not vary significantly over the year. “Annual air temperatures range from a mean maximum of 77 °F to a mean minimum of 71.6 °F” (USGS, n.d., p.1) due to the constant solar radiation and seawater temperatures. The sunlight differences are two hours between the longest and shortest day throughout the year (USGS, n.d). Solar Photovoltaic technologies that convert sunlight into electricity provide benefits to replace the use of fossil fuels to renewable energy. Puerto Rico’s weather has optimum characteristics to advance incorporating renewable technologies to provide “a relatively low cost electricity system” (Austin, Campbell, & Clark, 2017, summary page). Subsequently, renewable energies will reduce the use of fossil fuels in the near future (Holloway, S. 2001).

2.2 Solar Photovoltaic Technology

The photovoltaic (PV) system composed of panels, battery charger controller, batteries, and an inverter does not require mechanical movements to generate electricity thus the system produces energy quietly (Catalin-Bogdan, Simona, & Spiru, 2012). The Analysis of Residential Photovoltaic Energy Systems (2012) research project highlights the minimum operating costs requirement to operate and maintain the system. “Regular cleaning of the panel surface” will enhance the system operation to its maximum efficiency as recommended by the manufacturer (Catalin-Bogdan et al., 2012). The energy generated by the PV panels passes through an interlaid load regulator (Catalin-Bogdan et al., 2012). After the interlaid regulator, the energy passes to the batteries because “the parameters of the electric current used to load the battery must be constant” (Catalin-Bogdan et al., 2012, p.144). Also, the energy generated passes through a controller followed to a rectifier for users that are "connected to the outlet terminals of the controller" (Catalin-Bogdan et al., 2012, p.X). The rectifier converts direct current to "alternative current with 220V and a frequency of 50Hz" (Catalin-Bogdan et al., 2012, p.144).

The "ground-mounted PV systems are usually the lowest cost option to install" considering $/DC-Watt basis (Mosey and Salasovich, 2011, p.4). The Ground-mounted PV systems used are Fixed-tilt and Single-axis tracking systems. (Mosey and Salasovich, 2011). The tilt is the "vertical angle between horizontal and the array surface" (Dunlop, 2012, p.49). The "Fixed-tilt systems is fixed at that same angle and the Single-axis tracking systems have a fixed tilt on one axis and a variable tilt on the other axis (Mosey and Salasovich, 2011, p.4). The "Roof-mounted PV systems are usually more expensive than ground-mounted systems" (Mosey and Salasovich, 2011, p.5. The roof provides additional area leaving ground areas for other purposes.

Photovoltaic (PV) uses "certain semiconductors to directly convert solar radiation into electricity" (Dunlop, 2012, p.4). Semiconductors are composed of "crystalline silicone, that are sensitive to sun light" (Dunlop, 2012, p.4) and produces direct current after sunlight exposition. Dunlop (2012) emphasizes using a "utility-connected system, which is found on commercial and residential buildings" and is usually located at the roof of the house or near a solar ground area (p.4). Figure 2.1 on page 9 shows a typical Utility-Connected PV system that integrates electrical components to "control and condition the Direct Current (DC) power" (Dunlop, 2012, p.5) received from the PV array to convert it to Analog Current (AC) for further utility use.

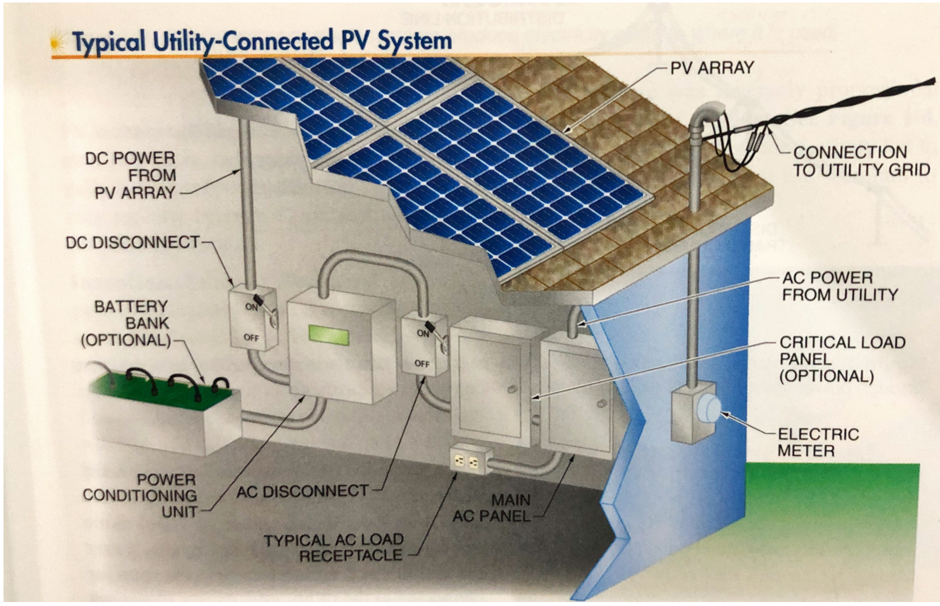

Figure 2.1 Typical Utility-Connected PV System

2.3 Photovoltaic Network Connection

Utility connected PV systems provide users independence compared to the electric grid and "reduces the consumer's vulnerability to utility power outages" (Dunlop, 2012, p.6). The design phase of a solar PV array system is crucial to determine the optimum amount of panel arrays required based on the amount of sun light exposure. The dimensioning of a PV system considers electric "annual production, depending on the location, orientation and inclination of the panels" (Catalin-Bogdan et al., 2012, p.144). Technological advances suggest the inclusion of PV systems to the distributed generation that can serve as a standalone power distribution or as a backup. Figure 2.2 on page 10 illustrates a distributed generation system that incorporates the use or renewable energy sources such as wind turbine and PV system interconnected with the grid substation.

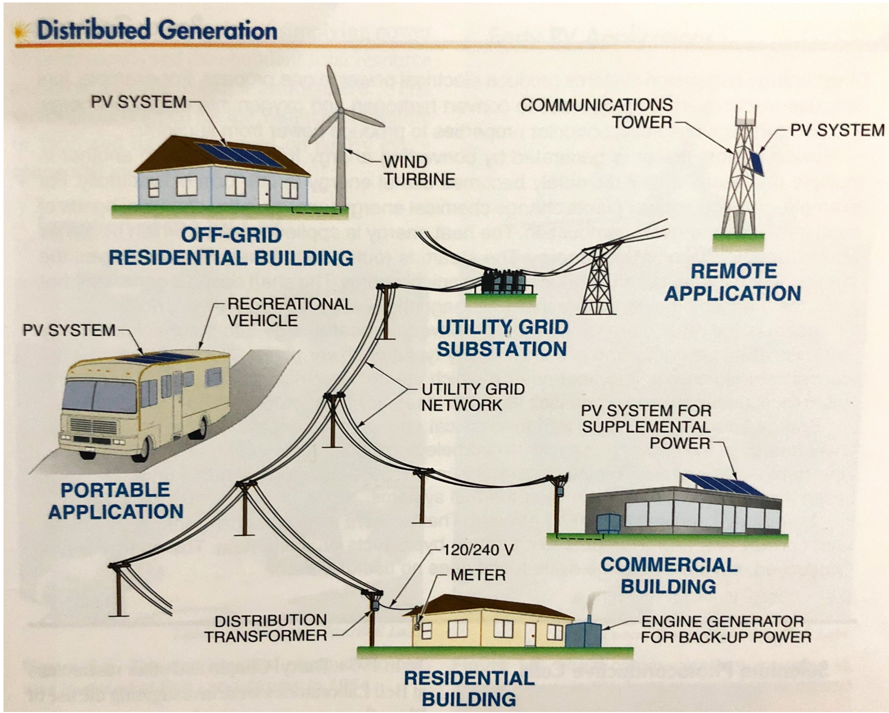

Figure 2.2 Distributed generation with renewable Energy sources

The crucial characteristic of a distributed generation system is the importance of creating "electrical power near the point of consumption" (Dunlop, P. 2012, p. 6). The design of short transmission lines avoids "electricity the losses from long transmission lines" up to the final user. The "excess power can be distributed to the grid if it is not needed" (Dunlop, P. 2012, p. 6) when the user has an interconnection with the grid while using the PV systems. The net metering Credit Rider, implemented in some locations, "mandated that the excess can be zapped into the public grid with the provider receiving the standard or full retail rate as a credit amount or a surplus" (Carrick, A 2016, p.1). The common drivers to transform the electric system to distributed generation are "lower costs, customer demand, environmental benefits and regulations" (Black & Veatch, 2020, p.1).

2.4 Puerto Rico Energy Generation Background

The energy generation from renewable energy options in Puerto Rico "mostly came from several small, privately owned wind and solar photovoltaic (PV) power installations, collectively providing less than 160 MW of capacity" (Campbell et al., 2017. p.6).

Puerto Rico has a combination of wind turbines and solar photovoltaic systems to generate renewable energy and coal, natural gas and petroleum from fossil fuels as reported by the U.S. Energy Information Administration (2019). Figure 2.3 provides an overview of the Puerto Rico power generating locations and its energy source (Gallucci, 2018).

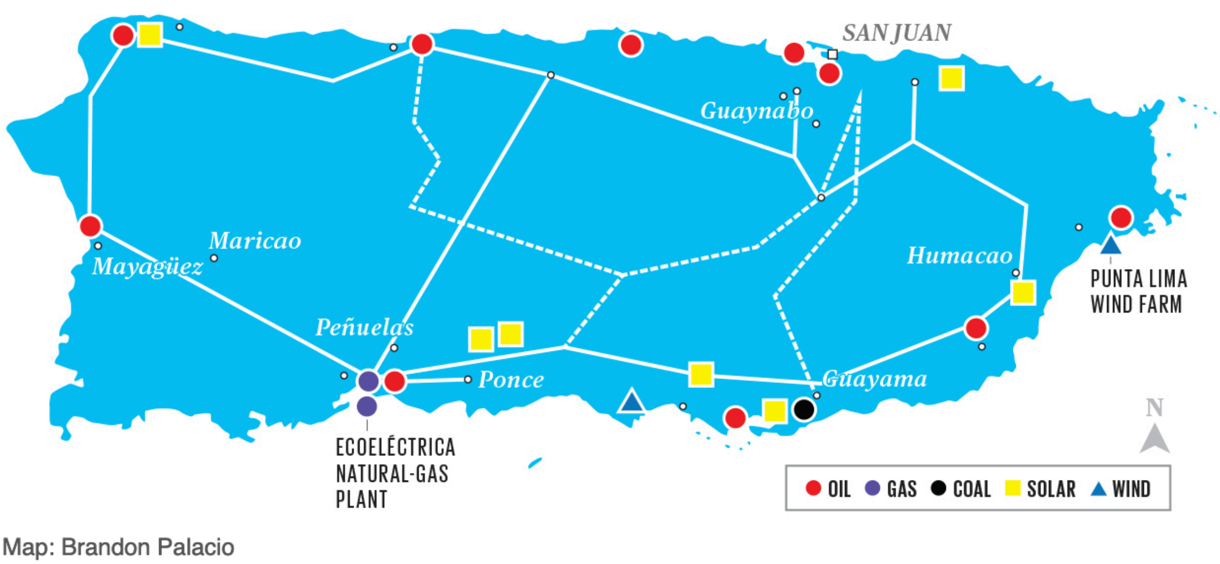

Figure 2.3 Puerto Rico Power Generation Overview

The Island uses "some renewable resources in the form of solar, wind, hydropower, and biomass but relies primarily on imported fossil fuels to meet its energy needs" (EIA, 2019, p.1). Table 2.1 on page 12 lists Puerto Rico energy generation power plants from fossil fuels as reported by the U.S. Energy Information Administration in 2019.

Table 2.1 Puerto Rico Energy Generation Power Profile from fossil fuels

Plant	**Capacity**
San Fermin Solar Farm Hybrid	Petroleum = 4 MW
Mayaguez Plant	Petroleum = 220 MW
Cervecera de Puerto Rico	Petroleum = 1.9 MW
Cambalache Plant	Petroleum = 241.5MW
Holsum de Puerto Rico, Inc.	Petroleum = 2.6 MW
Palo Seco Plant	Petroleum = 479.4MW
HIMA San Pablo Bayamon	Petroleum = 4.5 MW
Central San Juan Plant	Petroleum = 783.9MW
HIMA San Pablo Cupey	Petroleum = 1.2 MW
HIMA San Pablo - Caguas	Petroleum = 9 MW
Janssen Ortho LLC	Petroleum = 15.5MW
HIMA San Pablo Fajardo	Petroleum = 3 MW
Daguao	Petroleum = 42 MW
HIMA San Pablo Humacao	Petroleum = 1.6 MW
Jobos	Petroleum = 42 MW
AES Puerto Rico (Coal)	454.4 MW = Coal
Aguirre Plant	Petroleum = 1461.2 MW
Costa Sur	Natural Gas = 765.6 MW Petroleum = 200.9 MW
Ecoelectrica	Natural Gas = 580 MW

The EIA informed in 2019 that the "commercial sector consumes nearly half of the island's electricity, and the residential sector consumes just above one-third" (EIA, 2019, p.1). PREPA generates 62% electricity from petroleum-derived fuel at five PREPA-owned power plants: "Costa Sur, Aguirre, Palo Seco, San Juan, and Cambalache" (Campbell et al., 2017. p.5).

The EcoElectrica plant and Applied Energy Services (AES) facility provides electricity in accordance to a "private Independent Power Producers selling power under contracts to PREPA" (Campbell et al., 2017. p.5). The EcoElectrica plant is "fueled by natural gas from imported liquefied natural gas and the AES facility is fueled by imported coal" (Campbell et al., 2017, p.5).

PREPA's power generating facilities network connections consist of "2,478 miles of lines that deliver power from generating stations to 334 transmission and sub transmission substations" (Desai, N, Falcone, T., Hamm, J., McAvoy, J., Pizarro, P., Quinones, G. & Walker, B., 2017, p. 16). Puerto Rico transmission system consists "of 230kV overhead lines that form an approximate loop around the perimeter of the island" (Desai, N, et al. 2017, p. 16). The transmission line crosses long distances "from south to north" where the "230kV network connects to an extensive 115kV transmission system" that supplies power throughout the island (Desai, N, et al. 2017, p. 16). The Build Back Better Steering Committee (2017) acknowledged that "PREPA's transmission lines damaged during the storms were constructed decades ago". The "15% of the transmission lines are built to a mid-Category 4 criteria and the remaining 85% are built to lesser standards" (Desai, N, et al. 2017, p. 16), which demonstrates the vulnerability of a resilient and robust power system in Puerto Rico during catastrophic events.

The "electricity generation in Puerto Rico has shifted toward heavier reliance on petroleum after two earthquakes that struck 9 miles off the southwest coast of Puerto Rico" (EIA, 2020, p.1). The earthquakes affected Costa Sur power plant, which primarily use natural gas for electricity generation (EIA, 2020). The power plant damages "caused widespread power outages, and approximately 900,000 of Puerto Rico's 1.5 million customers lost power" (EIA, 2020, p.1). The "monthly power generation on the island was 17% lower in January 2020 than it was in December 2019 because of the outages" (EIA, 2020, p.1). The "Costa Sur power plant in generated 21% of the island's power and represented 52% of its natural gas-fired electricity generation" (EIA, 2020, p.1). The loss of the Costa Sur plant and the reduced generation from the natural gas-fired EcoEléctrica power plant, "shifted Puerto Rico's power supply to predominantly petroleum-based generation" (EIA, 2020, p.1). The petroleum dependency has increased from "60% of generation in the first three months of 2020" compared with "38% in 2019" (EIA, 2020, p.1). The Natural gas-fired generations decrease to "17% of total generation compared with 41% in 2019" (EIA, 2020, p.1). The energy generation from "Coal, renewables, and other generation sources have largely maintained the same shares" (EIA, 2020, p.1).

The small power generator has been introduced to the Island of Puerto Rico as a "temporary last line of defense for maintaining some of the security and safety of modern life" (Nussey, B. 2019, p.1). The independent power generators "require a constant supply of fuel" and are "not designed to run continuously" (Nussey, B. 2019, p.1). The power generators require constant refuel of gasoline or diesel, which costs "hundreds of dollars a month in fuel" while waiting for grid restoration (Nussey, B. 2019, p.1).

Figure 2.4 demonstrates de shift and increase of petroleum resources to meet customer needs as a result of the gas-fired EcoEléctrica damages.

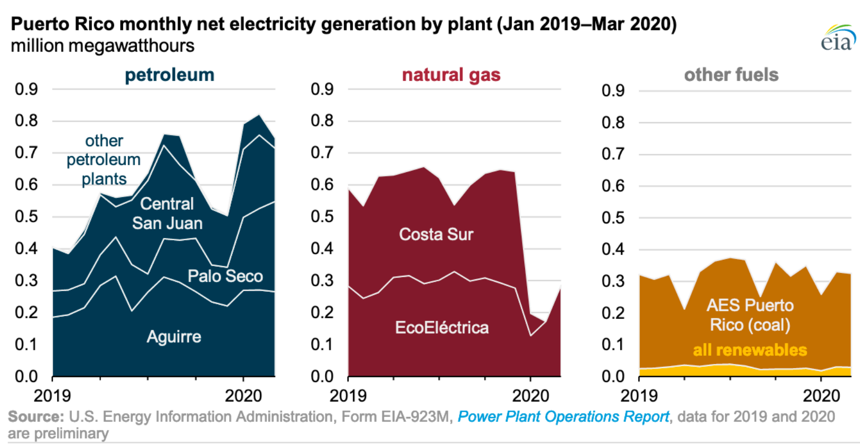

Figure 2.4 Puerto Rico's Net Electric Generation from 2019 to 2020

2.5 Renewable Energy Targets for Puerto Rico

A solar PV system is an attractive alternative for individuals who benefit from solar power and avoid depending on vulnerable electric systems. People “assume that these systems are too expensive for their application” (Dunlop, P. 2012, p. 426) and continue depending and paying the costs of electricity provided by PREPA. Puerto Rico needs years of work, governmental enforcement and PREPA re-organization to meet 100% Renewable energy sources.

The Solar Photovoltaic systems are the “least intrusive renewable energy resource technology” (Colucci, Irizarry-Rivera and O’Neill, 2008, p.12). Considering “Puerto Rico’s high population density and historic single family housing trends, approximately 65% of residential roofs can provide the total electrical energy (Colucci, Irizarry-Rivera and O’Neill, 2008, p.13). Puerto Rico’s weather characteristics for “energy generation potential is so significant that even 10% of the households can provide close to 20% of the overall energy demand” (Colucci, Irizarry-Rivera and O’Neill, 2008, p.13). The economic incentives are critical to support low-income families affordability to transition from the electric grid to renewable energy sources on their own (Colucci, Irizarry-Rivera and O’Neill, 2008). Colucci, Irizarry-Rivera and O’Neill continued the research study “Achievable Renewable Energy Targets” up to 2011 to show that “Puerto Rico has the resources necessary for energy self sufficiency”. Figure 2.5 on page 16 roadmap the complete elimination of fossil fuel dependency in 2027.

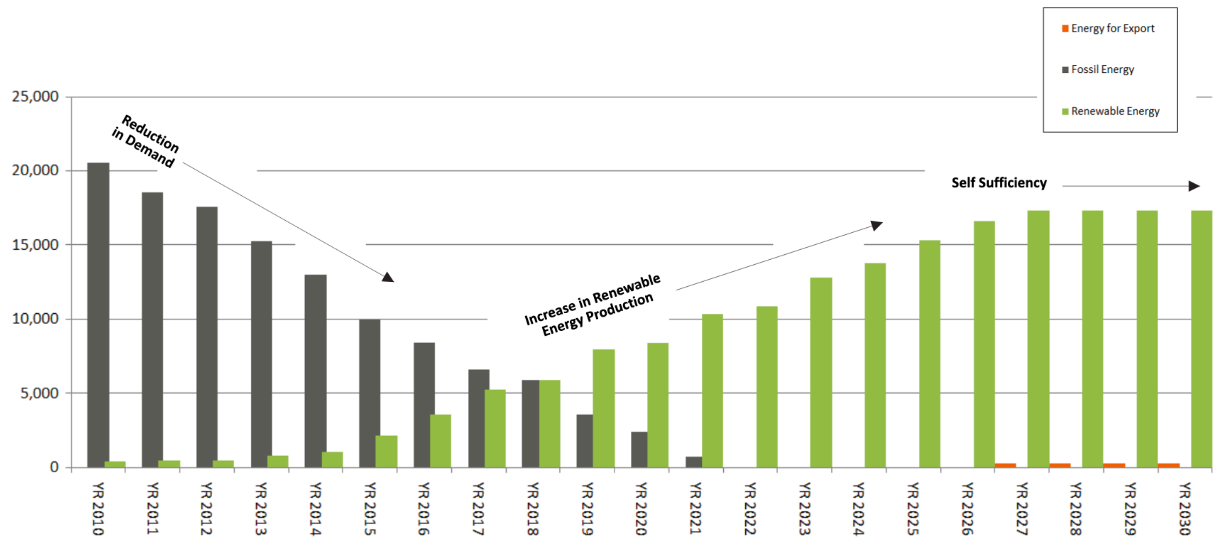

Figure 2.5 Puerto Rico's Net Electric Generation from 2019 to 2020

Several factors and variables influence the fossil fuel dependency transition to renewable energy sources. The factors or variables are Public and Private Partnerships, Pro-renewable energy government leadership in Puerto Rico, and U.S. Federal funding.

Puerto Rico Island has over 30 landfills that are suitable for solar PV system placement (Mosey and Salasovich, 2011). Mosey and Salasovich performed a screening and feasibility study in 2011 to evaluate and identify landfills sites with the "most potential for solar PV systems".

The landfills screening study considered infrastructure around the site such as roads and transmission lines. Mosey and Salasovich (2011) also considered screening criteria such as solar resource availability, acreage of the site, distance to graded road, distance to transmission lines, and slope of the site. Puerto Rico have adequate solar resource availability for a solar PV system but "the minimum acreage for a high potential landfill is 14 acres" (Mosey and Salasovich, 2011, p.9). Mosey and Salasovich identified a total of 16 landfills as high potential sites for solar PV in Puerto Rico. The research study recommended Public-Private ownership to provide the "most feasible way for a system to be financed on these sites" (Mosey and Salasovich, 2011, p.44).

2.6 Renewable Energy Worldwide

Sydney is an example of commitment and resilience toward eliminating "200,000 tonnes of CO_2 emissions from entering the atmosphere over the next 10 years" (Keck, 2020, p.1). Solar and wind technologies will power "115 buildings, 75 parks, 23,000 streetlights, and several sport facilities" (Keck, 2020, p.1). The solar electricity generation is a growing, multibillion dollar industry, but solar's share of the total energy market remains rather small" (NAE). The renewable energy sources estimate one percent of the total energy consumption, compared with the 85 percent from oil, natural gas, and coal (NAE). The fossil fuels cannot remain the dominant sources of energy forever since its use exacerbates air and water pollution problems (NA.).

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Research Environment

Puerto Rico uses "some renewable resources in the form of solar, wind, hydropower, and biomass but relies primarily on imported fossil fuels to meet its energy needs" (EIA, 2019). The research study evaluated the existing electric power sources against accessible and affordable renewable energy options. Puerto Rico's constant solar radiation throughout the year offers attractive alternatives toward moving to Photovoltaic technologies thus reducing energy dependence on fossil fuels. This research study quantified the 98% fossil fuels energy dependency and evaluated renewable energy options in Puerto Rico. The transition to renewable energy alternatives supports the reduction of carbon dioxide emissions to the environment and the National Academy of Engineering Grand Challenges of "Making Solar Energy Economical". There will be a reduction of available fossil resources in the future and renewable energy technology is an environmentally clean option. The research environment embody Puerto Rico energy consumption per source, current renewable energy generation, and future PV system projects.

3.2 Research Variables

The following research variables validated the use of renewable energy alternatives to impact the current 98% fossil fuel dependency:

1. Public and Private Partnerships between PREPA and LUMA Energy Corporation.
2. Pro-renewable energy government leadership in Puerto Rico to address the Energy Public Policy to transition Puerto Rico's power system to 100% renewable energy sources by 2050.

3. U.S. Federal funding to support the transition from fossil fuels to renewable energy sources.
4. Casa Pueblo initiative and movement to energize and rebuild Puerto Rico's energy grid with 50% solar energy by 2027.
5. "Queremos Sol" group initiative that pursue Puerto Rico 100% transition to distributed solar and storage energy.

3.3 Research Samples and Participants

The Puerto Rico Electrical Power Authority "is the largest supplier of electricity in the Commonwealth" of Puerto Rico, which supplies 21 billion kWh as reported in 2016 by the EIA. The research population tested was the total annual energy generated in Puerto Rico from June 2015 to June 2020. The sample size included energy generated in Mega Kilo Watt-hour (mkWh) for Petroleum, Hydroelectric, Natural Gas, Coal, Photovoltaic, and wind. The study included energy providers that sell energy generation to the PREPA authority.

The renewable energy population included eight landfills located in several municipalities in Puerto Rico known as Cataño, Guayama, Guaynabo, Salinas, San Juan, Santa Isabel, Toa Alta, and Toa Baja. The "landfills with the highest potential for PV" generation were identified by Salasovich, J and Mosey, G. in 2011 and were used to forecast fossil fuel reduction if PV systems were installed.

3.4 Research Statistical Measures

The data collected for energy generation and PV energy output opportunities was quantitative statistical. The first statistical measure was the energy generated for Petroleum, Hydroelectric, Natural Gas, Coal, Photovoltaic, and wind sources from June 2015 to June 2020 in mkWh. The second statistical measure included the theoretical annual energy output (kWh) from PV systems installed in landfills municipalities located at Cataño, Guayama, Guaynabo, Salinas, San Juan, Santa Isabel, Toa Alta, and Toa Baja. The third statistical measure included reducing 10%, 25%, and 50% to the annual energy output (kWh) if residential households install PV panels. The fourth statistical measure included reducing 15% and 25% to the annual energy output (kWh) if public lighting transition to solar pole technologies. The data supported the development of a forecast that demonstrated the behavior of fossil fuel consumption over time. The fossil fuel forecast assumed that PV system's implementation occurred at the landfills recommended by Salasovich, J and Mosey, G. The study also presumed that the residential clients switched to PV system and the public lighting sector transition to solar pole systems.

3.5 Research Control Treatment Groups

The research study forecasted the theoretical fossil fuel behavior and the CO_2 emissions reduction considering PV installation. The study assumed the data obtained from the energy consumed from June 2015 to June 2020 while preparing the forecast.

3.6 Research Instruments

The following sources and tools provided the information to quantify the research study and are available online:

1. Energy generation (mkWh) retrieved from https://indicadores.pr.
2. Annual energy outputs (kWh) for different proposed landfills retrieved from the "Feasibility Study of Economics and Performance of Solar Photovoltaics in the Commonwealth of Puerto Rico" research study.

3. The U.S. Environmental Protection Agency (EPA) provided the Greenhouse Gas Equivalencies Calculator to quantify the CO_2 emissions.

3.7 Research Data Collection, Processes and Procedures

Puerto Rico data sets obtained from https://indicadores.pr/statistics supported in the analysis and quantification of the energy generation. Table 3.1 shows an example used to document the collected data of the energy consumed per source. The sources to consider are Petroleum, Hydroelectric, Natural Gas, Coal, Photovoltaic, wind, and other technologies.

Table 3.1 Puerto Rico Energy Generation Data

Year (June to June)	Energy Generation (mkWh)						
	Petroleum	Hydroelectric	Natural Gas	Natural Gas Purchased	Carbon Purchased	Photovoltaic Purchased	Wind Purchased
2020							
2019							
2018							
2017							
2016							

Graphs visually illustrated the amount of energy documented in Table 3.1 to represent the too numerous mkWh. Figure 3.1 on page 22 shows an example of the 2D Column Graph used to demonstrate Puerto Rico energy generated data from 2015 to 2020 obtained from the https://indicadores.pr/statistics.

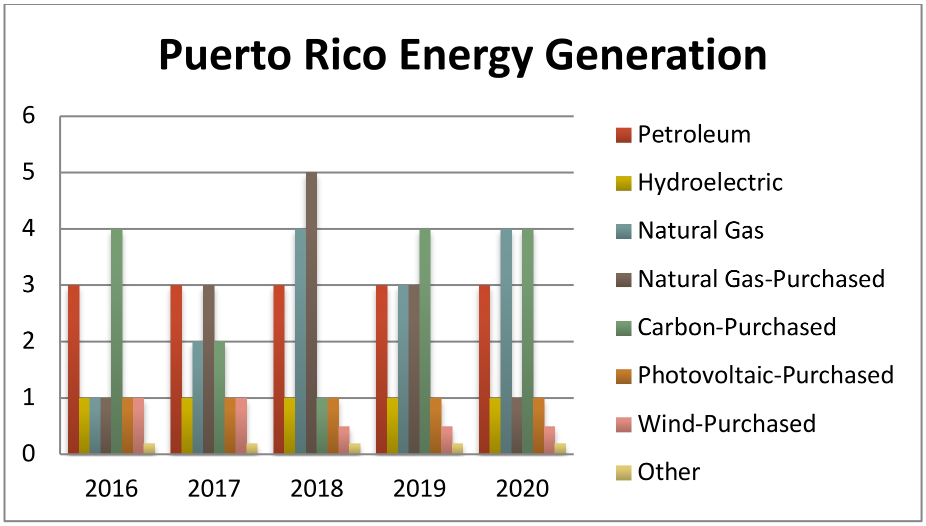

Figure 3.1 Puerto Rico Energy Generation

The "Feasibility Study of Economics and Performance of Solar Photovoltaics in the Commonwealth of Puerto Rico" research study specified data of the annual energy outputs (kWh) for different landfill sites (Mosey and Salasovich, 2011). Table 3.2 illustrates the format used to document each landfill site's collected data according to the PV system design technology.

Table 3.2 Annual Energy Output (kWh) per Landfill Site

Landfill Site	**Annual Energy Output (kWh)**		
System Type	**Crystalline Silicon—Fixed Tilt**	**Crystalline Silicon—Single-axis Tracking**	**Thin Film—Fixed Tilt**
Cataño			
Guayama			
Guaynabo			
Salinas			
San Juan			
Santa Isabel			
Toa Alta			
Toa Baja			

Figure 3.2 illustrates an example of a 2D Column Graph for the annual energy output using different PV system types (Mosey and Salasovich, 2011).

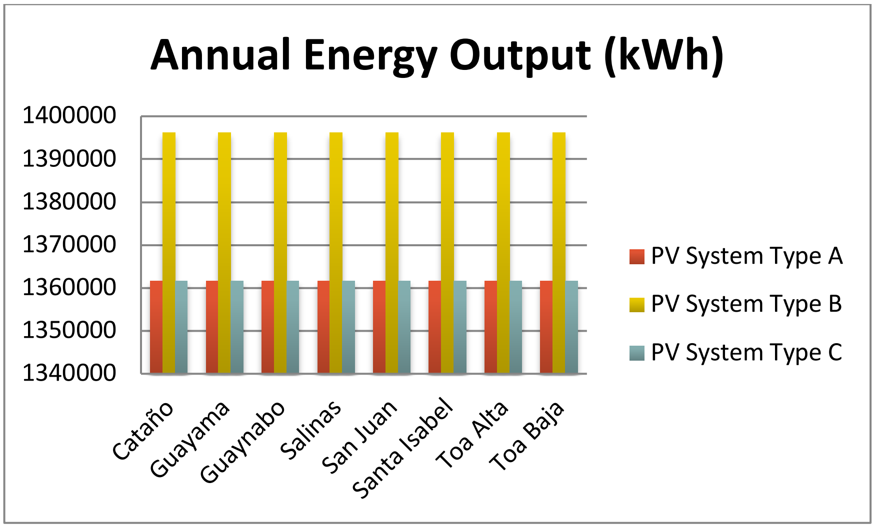

Figure 3.2 PV System Theoretical Annual Energy Output (kWh)

Different forecast graphs illustrated the theoretical fossil fuel behavior to include the transition to renewable energy sources. The illustrations considered PV systems installed at the evaluated landfill sites and that residential houses and public lighting transitioned to solar systems. The Greenhouse Gas Equivalencies Calculator provided by the U.S. Environmental Protection Agency (EPA) calculated the CO_2 emissions equivalent to the amount of fossil fuels generated.

3.8 <u>Limitations and De-limitations of the research</u>

The research study limitations focused on the collected energy data from previous years for the Island of Puerto Rico. The limit for annual energy output (kWh) data was the landfills suitable for the solar PV system as part of the screening and feasibility study performed by Mosey and Salasovich. The study included additional limits that considered residential solar PV panels and solar pole technologies for public lighting.

CHAPTER 4. RESULTS

4.1 Puerto Rico Power System Generation

The research study evaluated Puerto Rico's Island current power system status and the transition to an economical renewable option considering weather benefits for solar photovoltaic. Throughout the year, Puerto Rico's weather conditions provide effective and affordable energy alternatives after catastrophic events such as hurricanes or earthquakes. The study assessed Petroleum, Hydroelectric, Natural Gas, Coal, Photovoltaic, wind, and other technologies in Puerto Rico from June 2015 to June 2020. The energy consumption data sets were retrieved from https://indicadores.pr, as described in figure 4.1 for five years.

Figure 4.1 Access to the Puerto Rico energy consumption data

Table 4.1 on page 25 summarizes Puerto Rico's annual energy generation in a million-kilo Watt-hour (mkWh) from June 2015 to June 2020, reported by PREPA. The data displayed includes the energy generated by PREPA and the energy purchased to other companies through Public and Private Partnerships by source per year. The data consists of current renewable energy sources such as photovoltaic, Hydroelectric, and wind, and fossil fuel sources such as petroleum, natural gas, and carbon.

Table 4.1 Annual Energy Generation for Puerto Rico (mkWh)

Year (June to June)	Energy Generation (mkWh)						
	Petroleum	Hydroelectric	Natural Gas	Natural Gas Purchased	Carbon Purchased	Photovoltaic Purchased	Wind Purchased
2015 to 2016	10363.81	53.60	3653.67	3288.08	3202.47	104.41	223.69
2016 to 2017	9889.94	86.27	3196.04	3287.64	3451.99	165.18	190.15
2017 to 2018	7988.41	38.80	2326.20	2581.27	3451.99	165.18	85.52
2018 to 2019	7687.06	31.20	3987.68	3240.99	3060.95	170.38	163.75
2019 to 2020	8873.67	47.57	2603.13	3255.51	3586.11	252.76	143.49

Figure 4.2 illustrates the significant differences between Petroleum, natural gas, and carbon compared to renewable energy sources. The data confirms that PREPA relies on fossil fuels as the primary source of power generation on the Island (EIA, 2019). The collected data shows that Petroleum, Natural Gas, and Carbon, known as fossil fuels, lead the energy consumption primary source in the Island of Puerto Rico.

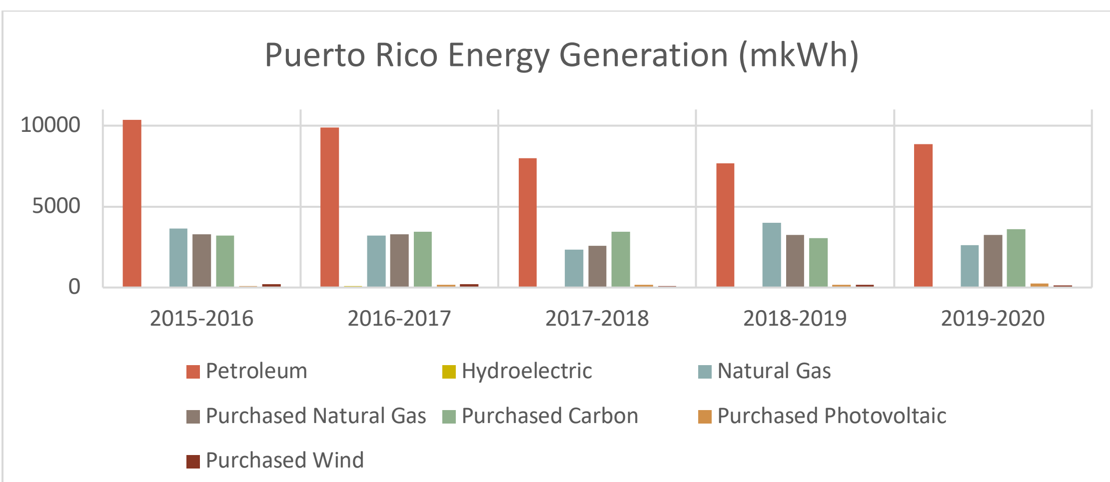

Figure 4.2 Puerto Rico Energy Generation

4.2 Renewable Energy Alternatives

The lack of effective and affordable energy substitutes after Hurricane Maria resulted in a mortality increase of 4,970 residents (Verma, Murray, and Mamdani, 2018). The lack of electricity from Petroleum sources caused chaos after the storm. The time it took to repair the electrical grid wasn't enough to prevent 4,970 residents' deaths. The power grid restoration must consider "vulnerabilities of modern electrical networks and on the emerging technological options for minimizing those vulnerabilities" (Gallucci, 2018, p.1). Energy substitutes such as Renewable energy sources during catastrophic events minimize electrical vulnerabilities.

The National Renewable Energy Laboratory (NREL) published a study that assessed the solar photovoltaic opportunities at several landfill sites in Puerto Rico. Table 4.2 summarizes the screening and feasibility study performed in 2011 by Mosey and Salasovich, which evaluated and identified landfill sites in Puerto Rico with the "most potential for solar PV systems".

Table 4.2 Annual Energy Output (kWh) per Landfill Site

Landfill Site	**Annual Energy Output (kWh)**		
System Type	**Crystalline Silicon—Fixed Tilt**	**Crystalline Silicon—Single-axis Tracking**	**Thin Film—Fixed Tilt**
Cataño	1,361,700	1,396,143	560,700
Guayama	720,900	698,072	320,400
Guaynabo	480,600	498,623	160,200
Salinas	Not feasible	Not feasible	Not feasible
San Juan	12,015,000	12,365,838	5,126,400
Santa Isabel	961,200	997,245	400,500
Toa Alta	560,700	498,623	240,300
Toa Baja	801,000	1,296,419	560,700

The NREL feasibility study considered ground-mounted PV systems based on the lowest installation cost option. Seven landfills out of eight considered feasible to install ground Photovoltaic Panels supported the transition to renewable energy generation initiatives. The Salinas site did not provide optimum characteristics due to the sloped landfill encountered by Mosey and Salasovich. Figure 4.3 shows the data collected, reflecting that the Crystalline Silicon system type offers the highest annual energy output compared to the Thin Film at each site. The differences between the Crystalline Silicone system type refers to the sunlight tracking angle and axis to obtain the highest sunlight throughout the year. Guayama and Toa Alta landfill sites generate the highest annual energy output using the fixed-tilt configuration. In contrast, Cataño, Guaynabo, San Juan, Santa Isabel, and Toa Baja benefit from single-axis tracking.

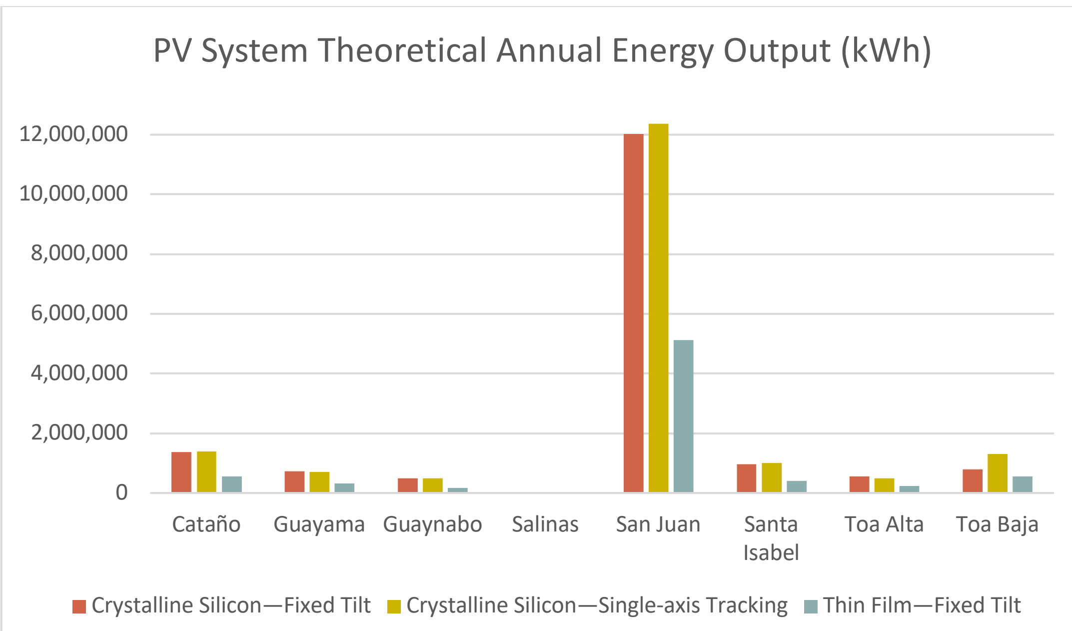

Figure 4.3 Photovoltaic (PV) Annual Energy Output – Feasibility Study

The overall or total annual energy output considered the maximum energy output obtained from each site based on the system type used. Table 4.3 on page 28 summarizes the highest energy output potential based on material system type and sunlight tracking mechanism. The analyzed landfill sites have a total capacity to generate 17,835,868 kWh per year using PV systems.

Table 4.3 Highest Annual Energy Output (kWh) per Landfill Site

Landfill Site	Annual Energy Output (kWh)
Cataño	1,396,143
Guayama	720,900
Guaynabo	498,623
San Juan	12,365,838
Santa Isabel	997,245
Toa Alta	560,700
Toa Baja	1,296,419
Total Annual Output	**17,835,868**

The original energy generated from fossil fuel sources incorporated the PV system's annual energy output from the seven landfill sites. The energy consumption data sets available in Table 4.1 on page 25 were converted from mkWh to kWh by multiplying by 10^6 as shown in figure 4.4 to align units between fossil fuel generation and PV solar system capacity.

$$\text{Energy Generation (mkWh)} * 10^6 = \text{Energy Generation (kWh)}$$

Figure 4.4 Energy Consumption Conversion (mkWh to kWh)

Table 4.4 on page 28 and 29 lists the yearly fossil fuel generation, the total annual output from PV systems, and the energy reduction if PV systems exist.

Table 4.4 Highest Annual Energy Output (kWh) per Landfill Site

Year (June to June)	Total Fossil Fuel Generation	Total Annual Output from PV	PV Implementation
2015 to 2016	20,508,033,082.60	17,835,868	20,490,197,214.60
2016 to 2017	19,825,611,102.70	17,835,868	19,807,775,234.70

Table 4.4 Highest Annual Energy Output (kWh) per Landfill Site (Cont)

Year (June to June)	Total Fossil Fuel Generation	Total Annual Output from PV	PV Implementation
2017 to 2018	16,347,879,019.00	17,835,868	16,330,043,151.00
2018 to 2019	17,976,685,212.00	17,835,868	17,958,849,344.00
2019 to 2020	18,318,416,593.74	17,835,868	18,300,580,725.74

Figure 4.5 illustrates the amount of fossil fuel reduction if these Solar Photovoltaic (PV) landfills were operating between June 2015 to June 2020, thus supporting PREPA fossil fuel energy generation.

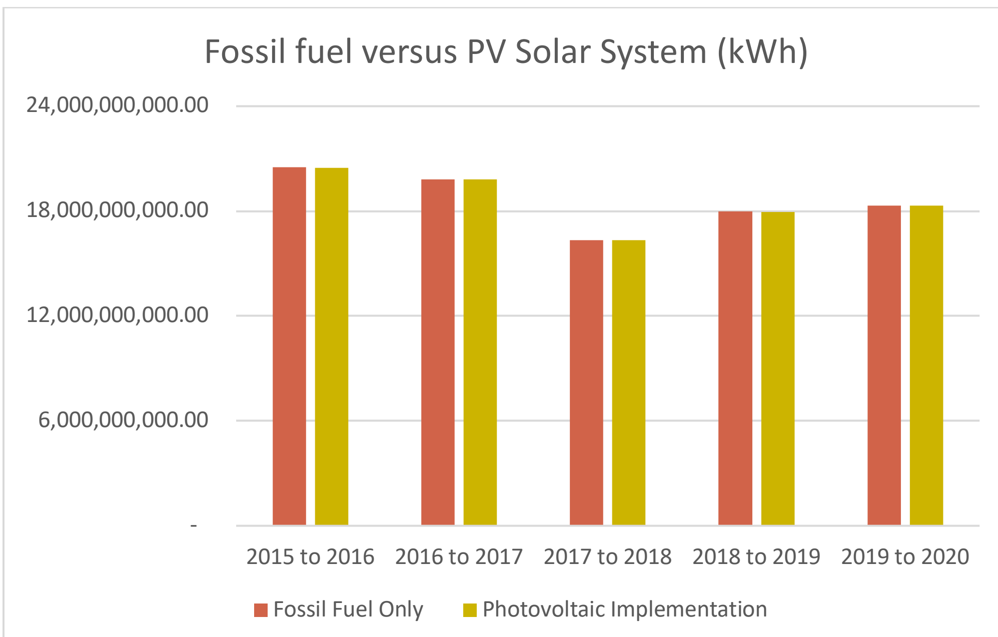

Figure 4.5 Fossil Fuel reduction with PV

The seven landfill sites considered as feasible for PV installation supports the transition to renewable energy but do not reduce fossil fuel usage significantly to achieve a 100% renewable energy sources by 2050.

Several sectors contribute to the energy consumption in Puerto Rico, and emerging technologies with practical applications exist to support the transition to an energy cleaner option. The major contributors to the energy consumption in Puerto Rico are the residential, commercial, industrial, public lighting, and agricultural sector. Colucci, Irizarry-Rivera, and O'Neill recommended that approximately 65% of the residential roofs provide the total electrical energy (Colucci, Irizarry-Rivera, and O'Neill, 2008). Figure 4.6 illustrates the fossil fuel forecast reduction considering 10%, 25% and, 50% if residential roofs provide electrical energy to the residential sector.

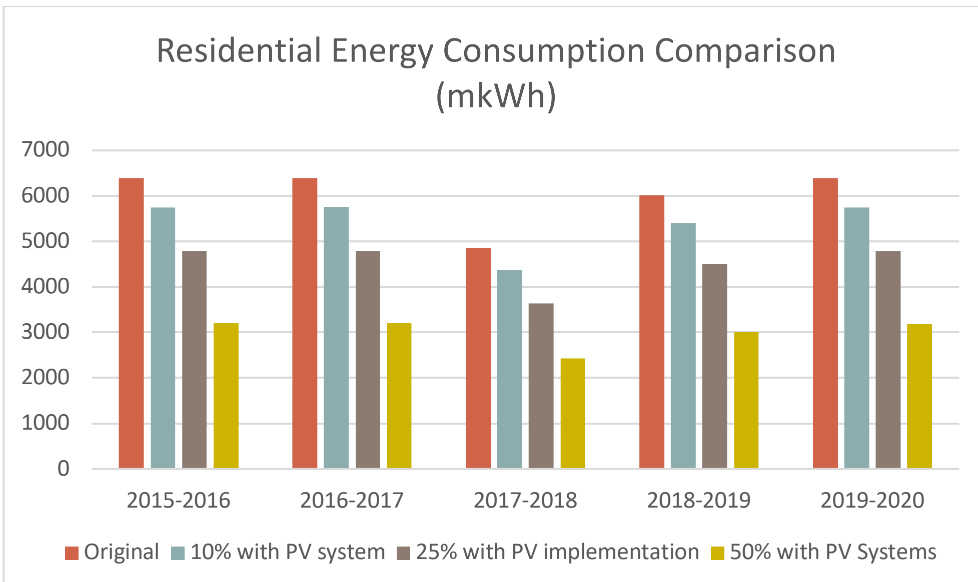

Figure 4.6 Residential Energy Consumption in Puerto Rico

The forecast calculation incorporating PV panels at the roof of households demonstrates a significant reduction of fossil fuel consumption considering Puerto Rico's weather conditions and characteristics. The fossil fuel reduction is evident and achievable, contemplating pro-renewable energy government leadership in Puerto Rico along with U.S. Federal funding to support household inversion costs. Figure 4.7 on page 31 shows the public lighting sector that contributes to fossil fuel consumption throughout the Island. New technologies such as solar public poles installation provide cleaner energy options to reduce fossil fuel consumption and support carbon dioxide emissions to the environment.

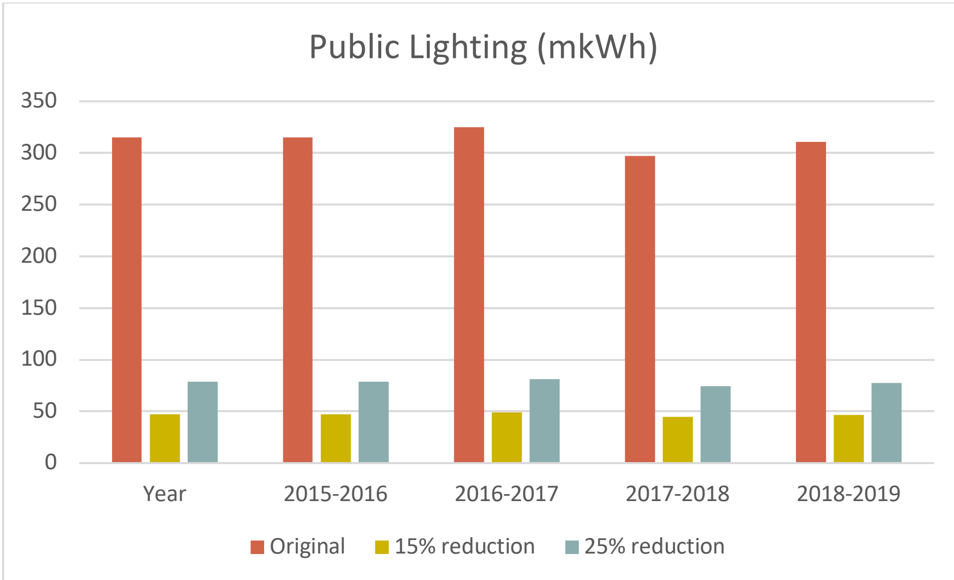

Figure 4.7 Public Lighting Consumption in Puerto Rico

4.3 Carbon Dioxide Emissions

The U.S. Environmental Protection Agency (EPA) Greenhouse Gas Equivalencies tool found in https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator calculated the Carbon dioxide emissions in metric tons, as shown in Table 4.5 on page 31 and 32.

Table 4.5 Carbon Dioxide Emissions (Metric Tons)

Carbon Dioxide Emissions (Metric Tons)							
Year	PREPA Fossil Fuel Generation	PV Landfill Implementation	Residential 10% Reduction	Residential 25% Reduction	Residential 50% Reduction	Public Lighting 15% Reduction	Public Lighting 25% Reduction
2015 to 2016	14,500,000	14,487,389	4,065,644	3,388,037	2,258,691	189,483	167,191
2016 to 2017	14,017,500	14,004,889	4,067,458	3,389,548	2,259,699	189,366	167,088

Table 4.5 Carbon Dioxide Emissions (Metric Tons) (Cont.)

Carbon Dioxide Emissions (Metric Tons)							
Year (June to June)	PREPA Fossil Fuel Generation	PV Landfill Implementation	Residential 10% Reduction	Residential 25% Reduction	Residential 50% Reduction	Public Lighting 15% Reduction	Public Lighting 25% Reduction
2017 to 2018	11,558,604	11,545,994	3,089,254	2,574,378	1,716,252	195,455	172,461
2018 to 2019	12,710,236	12,697,625	3,828,068	3,190,057	2,126,704	178,469	157,473
2019 to 2020	12,951,853	12,939,243	4,063,125	3,385,937	13.5	186,665	164,704

The Greenhouse Gas Equivalencies Calculator tool converted the energy generated in kWh to CO_2 emissions. Figure 4.8 illustrates the amount of carbon dioxide emissions released to the atmosphere due to the current reliance on fossil fuel generation. The graph compares the original carbon dioxide emitted against carbon dioxide reduced if the PV system's installation occurs at the proposed landfill sites. The carbon dioxide does not significantly decrease the original amount to achieve a noticeable reduction.

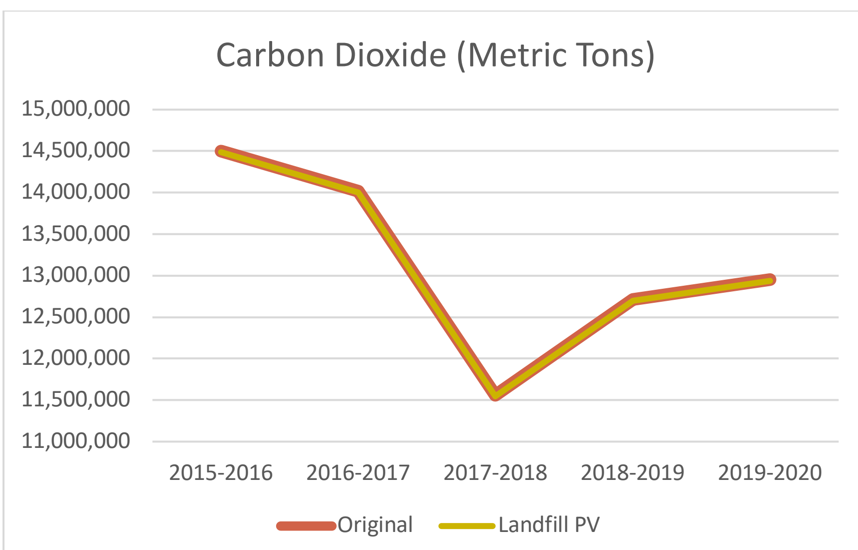

Figure 4.8 Carbon Dioxide emmissions – Original Fossil Fuel Generation

Figure 4.9 demonstrates a noticeable reduction of carbon dioxide emissions if 10%, 25% or 50% of the residential sector transition to solar photovoltaic technologies as their primary energy source.

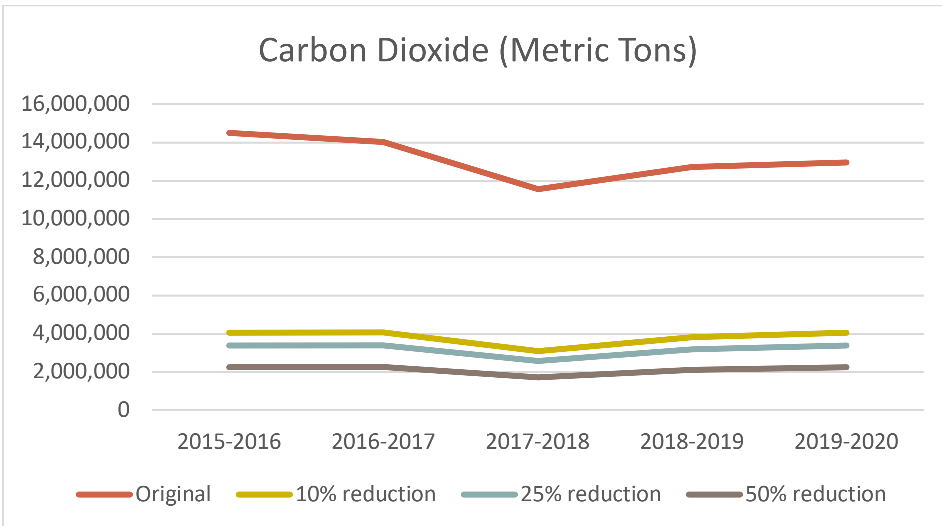

Figure 4.9 Carbon Dioxide emmissions – Fossil Fuel reduction for Residential sector

Figure 4.10 illustrates a significant reduction of carbon dioxide emissions resulting from implementing 15% or 25% of solar pole technologies instead of using fossil fuel for public lighting purposes.

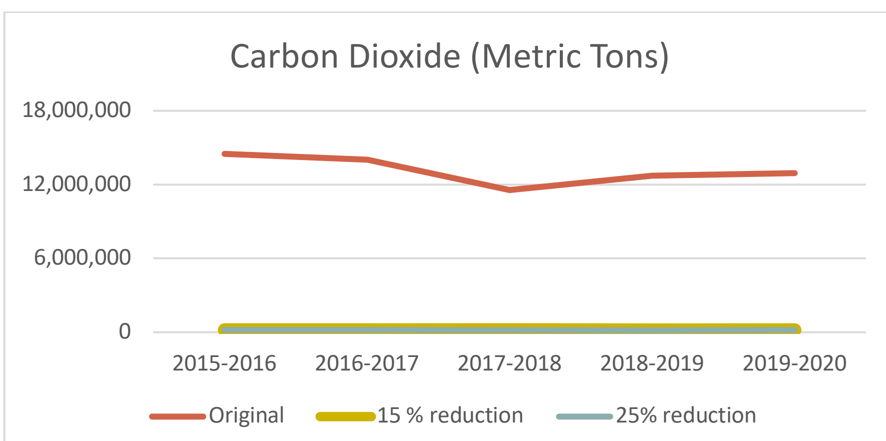

Figure 4.10 Carbon Dioxide emmissions – Fossil Fuel reduction for Public Lighting

4.4 Research Timeline

The research study quantified the fossil fuels energy dependency and evaluated renewable energy options in Puerto Rico. Figure 4.11 illustrates the timeline used to organize the research study data collection, data analysis, graphical development, and results analysis. The timeline included project execution per task and considered backup days to modify any roadblock or gaps. The backup days helped to obtain and analyze additional data for residential consumption and public lighting. The landfill sites proposed for PV installation showed a minimal impact on reducing fossil fuel usage. Therefore, leveraging additional renewable energy alternatives will accelerate Puerto Rico's dependence on petroleum; subsequently, reducing carbon dioxide emissions (National Academy of Engineering, 2019).

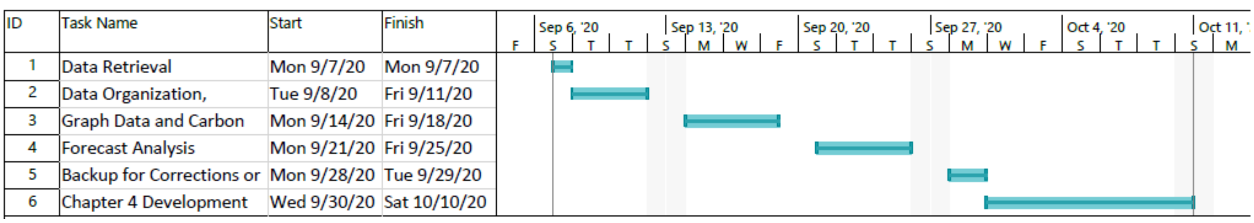

Figure 4.11 Data Analysis Timeline

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

The Puerto Rico Electric and Power Authority (PREPA) owns 80% of the energy generation capacity and controls the transmission and distribution of the Island (EIA, 2019). Puerto Rico's Island dependency on electric power and no energy substitutes available have provoked a risk to human life after catastrophic events. Hurricane Maria and the earthquakes' aftermath has raised the severe need to transform Puerto Rico's electric grid to renewable energy sources. Earthquakes and hurricanes have affected the physical infrastructure resulting in a delay in restoring the fragile system. Puerto Rico's location and stable weather conditions favor Solar Photovoltaic (PV) technologies as energy alternatives to fossil fuel consumption.

The research study evaluated Puerto Rico's Island current power system status and the transition to an economical renewable option considering weather benefits for solar photovoltaic. The study assessed and tabulated Petroleum, Hydroelectric, Natural Gas, Coal, Photovoltaic, and wind in Puerto Rico from June 2015 to June 2020. The analysis included eight (8) different landfills recommended by the National Renewable Energy Laboratory (NREL) as the highest potential of energy output using Solar Photovoltaic (PV). Also, PV panels at the roof of households and new technologies such as solar public poles were considered additional initiatives to provide cleaner energy options to reduce fossil fuel consumption.

The feasibility study, performed by the NREL, provided a theoretical energy output considering solar PV systems implemented at the identified landfills. The theoretical energy output incorporated into the energy generated in Puerto Rico from June 2015 and June 2020 shows the fossil fuel reduction while suing PV systems. The installation of solar PV systems for the residential and public lighting sector also contributed to fossil fuel reduction. The overall fossil fuel reduction resulting from PV system implementation resulted in an evident impact on reducing carbon dioxide emissions. Figure 5.1 illustrates the research study overview of data collected and the impact on fossil fuel reduction and carbon dioxide emissions.

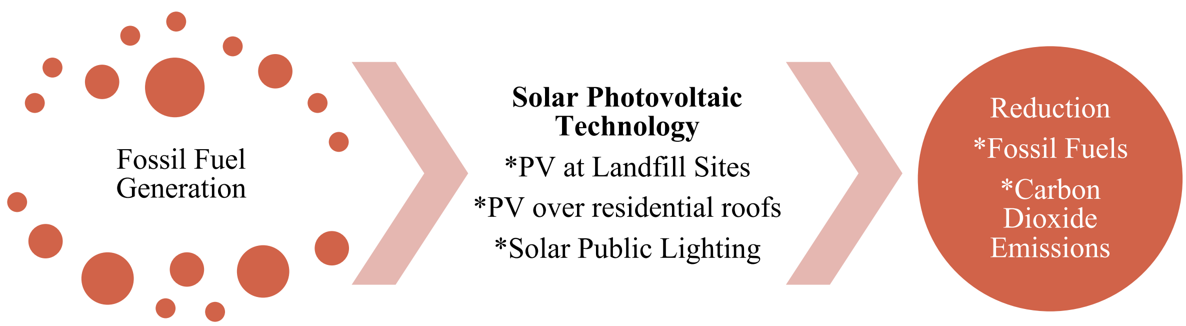

Figure 5.1 Research Study Data Analyisis Overview

5.2 Conclusions

The research study correlated the benefit of Photovoltaic solar systems to improve a cleaner and sustainable energy option than the energy generation from fossil fuel. The data gathered of energy generation in Puerto Rico showed a trend towards fossil fuel consumption over five years, 2015 to 2016. Several renewable energy options and sources exist, such as photovoltaic, hydroelectric, and wind, but are insufficient to mitigate fossil fuel use. The energy consumption in Puerto Rico relies on fossil fuels as the primary source, and no other competitors exist to provide other energy alternatives to clients nor public energy consumption. The bankruptcy situation at PREPA does not help restore the power grid appropriately nor provide the maintenance required to avoid a power blackout in the upcoming years.

The NREL provided key alternatives for improving and contributing to fossil fuel reduction by using landfills in Puerto Rico to install Photovoltaic solar panels. Solar PV systems offer the advantage of supporting fossil fuel reduction due to Puerto Rico's weather characteristics. Also, the low maintenance cost required for the PV panels makes solar systems attractive in locations where temperatures do not vary over the year.

The NREL recommended seven landfills in Puerto Rico as optimum for PV installation considering different solar panel materials. The research study used the recommended material panels capable of generating higher energy output. The solar PV installation supports the transition to renewable energy but does not significantly reduce fossil fuel usage to achieve 100% renewable energy sources.

The research study required additional renewable energy options to recommend a substantial reduction of fossil fuels contemplating PV technologies with other applications. Solar PV systems are a residential sector option for users who want to disconnect from PREPA electric consumption and keep the grid connection as a backup. This research study included three different percent options to anticipate the fossil fuel reduction if a predetermined number of households switch to solar photovoltaic panels. The analysis "Achievable Renewable Energy Targets" was used as a baseline to forecast the residential sector electric usage, which suggests 65% of houses with the capability to transition to solar PV technologies. The research study evaluated a range from 10% up to 50% of residents transferring from the electrical supply to the solar PV systems. The results showed a fossil fuel reduction of almost half of the current consumption considering PV systems implementation to 50% of the Puerto Rico households.

Solar public poles are another opportunity to reduce fossil fuel generation, considering that innovative technologies exist to substitute electric supply to public lighting. The 15% and 25% replacement of the total electric public poles to solar PV technology used in Puerto Rico and considered in this study results in a significant reduction in favorably to a fossil fuel reduction. Implementing solar PV systems to the seven landfills, the transition to almost 50% of Puerto Rico residents to PV systems, and the transition to solar public lighting positively impacts the carbon dioxide emissions to the atmosphere.

5.3 Recommendations

The research study recommendations link governmental decisions and elections occurring in the 2020 year. The Public and Private Partnerships between PREPA and LUMA Energy Corporation contribute to the transition of renewable energy sources but depends on federal energy funds to execute the contract statement. LUMA's contract statement establishes a power grid restoration to comply with the Puerto Rico Energy Public Policy Act to transition the electric power system to 100% renewable energy sources by 2050 (*Act No. 17-2019 S. B. 1121*, 2019). After Hurricane Maria and earthquakes, the lack of adequate and affordable energy substitutes demonstrates electrical vulnerabilities to recover after an electric shutdown event. An extent to federal funds to boost and increase residential transition to PV solar systems is critical to increasing households' interest. The recommendation towards the transition to solar public poles is to assign each municipal leader accountable for replacing available poles with solar PV systems. Also, transitioning governmental buildings in collaboration with the Leadership in Energy and Environmental Design (LEED) certification and rating system to enhance energy usage.

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