Design of a More Reliable Power Grid for Puerto Rico

FINAL PROPOSAL

sddec18-03

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Table of Contents

List of Definitions

Critical Loads

As a top priority when we are implementing the power grid using many different microgrids, the main focus for our power distribution will be areas that are more heavily populated and consists of more critical infrastructure. These important infrastructures or critical loads refer to hospitals, fire departments, police departments, emergency shelters, water treatment facilities for wastewater and drinking water. These are the critical loads that we want to ensure will have continuous power generation.

Distributed Energy Resources (DER)

Distributed generation, also distributed energy, on-site generation or district/decentralized energy is electrical generation and storage performed by a variety of small, grid-connected devices referred to as distributed energy resources. These distributed energy resources will be implemented in the microgrids which will consist of solar energy, wind energy, and natural gas as a backup power supply throughout the island.

Microgrid

A small network of electricity users with a local source of supply that is usually attached to a centralized national grid but is able to function independently.

PREPA (Puerto Rico Electric Power Authority)

Electric power company and government-owned corporation of Puerto Rico responsible for electricity generation, power distribution, and power transmission on the island. Also known as Autoridad de Energía Eléctrica (AEE)

1 Introductory Material

1.1 Problem Statement

Over 80% of Puerto Rico's power grid was recently destroyed in hurricanes Irma and Maria. However, even before these storms ravaged the electric utilities on the island country, a lack of maintenance and upgrades under unstable and underfunded PREPA leadership led to a grid susceptible to collapse, with many natives citing downed power lines and power outages as a normal occurrence. As a design team, we aim to design a power grid for Puerto Rico that is more reliable and makes maintenance easy and possible should other natural disasters occur.

Our proposed solution encompasses many areas of the country's current electrical utility system, including updated generation, transmission, and reliability measures. We will also discuss economics and policies relating to the construction and maintenance of the updated grid.

1.2 Operating Environment

The proposed design will be exposed to rain, severe tropical storms and hurricanes, and temperatures averaging between 61˙F and 80˙F, with maximum and minimum temperatures of over 100˙F and below 40˙F, respectively. The main consideration for this project design is creating an energy system robust enough to handle tropical storms, hurricanes, and other natural disasters when paired with proper maintenance.

1.3 Intended Users and Intended Uses

The intended users of this plan include utility companies and legislators in Puerto Rico. This proposed solution will combine research, grid design, economic suggestions, and additional area improvements to revamp Puerto Rico's energy market.

Firstly, the proposed solution will discuss the redesign of the current power grid. This outline introduces solutions such as interconnected microgrids, the addition of both large-scale and distributed solar and wind resources, added energy storage, and a shift to natural gas generation made possible by a natural gas port and pipeline to population centers.

Secondly, this plan will discuss the socioeconomic market surrounding electric utility in Puerto Rico. The suggested changes aim to change the way utilities are subsidized in turn generating revenue and cutting losses for the current bankrupt system as well as suggesting policy updates to encourage maintenance of the updated energy system.

1.4 Assumptions and Limitations

Assumptions	Limitations
Current political preferences and procedures will not be taken into consideration within this proposal.	This power grid redesign must fall under feasible budgetary limitations.
Contractual obligations or effects due to contracts will not be taken into consideration within this proposal.	This power grid must withstand temperature swings and severe weather common in Puerto Rico.
Population measurements will be approximated using the most recent census data.	The feasibility of this power system will be tested by economic and numerical means.

1.5 Expected End Product and Other Deliverables

At the end of our project, we aim to have a written proposal encompassing both the technical and economic factors associated with Puerto Rico's power grid.

The components of the physical, technological redesign will encompass the entirety of the country and discuss the current grid, technologies, and generation systems. From this basis, the proposal will suggest the addition of solutions such as large scale and distributed renewable energy resources, increased energy storage, interconnecting microgrids, industrial natural gas generation, and supplementary distributed turbines. The grid shall be designed with natural disasters in mind by proposing components that can withstand severe weather.

The economic redesign will propose solutions related to subsidization of utilities in the commercial, industrial, and residential sectors. The cost and price of energy will be discussed and a solution related to these findings will be presented. This economic report will also encompass the costs and profits associated with installation of new physical energy components such as solar and wind farms, gas and diesel turbines and natural gas generation facilities. Maintenance policies and budgets will be presented as well.

Overall, this written proposal will describe the proposed technologies along with their locations, specifications, and costs, as well as outline the proposed economic model to be adopted to best profit the country. The plan will also have cost outlines for implementing this plan. The combined report will be delivered by December 3, 2018.

2 Proposed Approach and Statement of Work

2.1 Objective of the Task

After recent natural disasters, a majority of Puerto Rico's power lines, substations, and generation plants were left broken and unusable, leaving the population living without electricity in their homes for months. However, the power grid of the country was also in a horrible state before the natural disaster hit due to improper management of the current power grid.

Therefore, this task focuses on the current power grid of Puerto Rico with the goal of making it more reliable and more effective. The focus of this project is creating a better economic and physical design of the power grid and electric utility market to ensure the entirety of the island will constantly be supplied by with electricity, including during hurricanes and other natural disasters. Our team plans to design a power grid that not only provides constant electricity to the island, but also can be repaired quickly and cheaply to minimize the impact of a natural disaster on the power grid.

We will carry out this task in two main sections: one focusing on the physical and technical component of the grid, and the other focusing on the economics and policies relating to the power system.

On the technological side, we have four main areas of focus: generation and transmission, renewable energy, energy storage, and microgrids. The basis of our proposal revolves around the construction of a natural gas deliquification port on the east coast of the island and subsequent updating of two of Puerto Rico's oil-run generating facilities. The introduction of coal turbines and storage to allow backup energy fuel in blackout situations.

Both wind and solar resources will be introduced. This decision was partially based on solar irradiance data and partially on the proven effectiveness for Tesla after they had implemented them at San Juan's Hospital Del Nino (BBC, 2017), and with AES, whom we have been in contact with throughout this project. Onshore and offshore wind will play a role, with average coastline winds and crest winds allowing for maximum function year round.

Whenever there are any renewable energy involved in a design, we must also implement energy storage. Current technologies are expensive to implement (considerably more so than natural gas, which ranges from $5 - $15 per thousand cubic feet (U.S. Energy Information Administration, 2018)), leading us to emphasize that natural gas is the most reasonable source of energy to start with as the 'base' of our project.

Lastly, we will be encouraging increasing the interconnectivity of the current grid on a community scale and transmission scale. By adding a fourth transmission loop and connecting communities and generation stations to various surrounding areas through independent microgrids, the risk of blackouts, which currently happen at a rate of 4-5 times more than in the average American Household (Vives, Ruben, and Molly Hennessy-Fiske, 2017), and the length of these blackouts, will be reduced due to added connections. The addition of distributed renewable energy resources paired with energy storage and backup natural gas turbines for natural gas energy will also allow for communities and critical loads to remain connected to power even if connecting transmission lines experience outages and assist in providing power to connecting communities should it be required.

2.2 Functional Requirements

2.2.1 Natural Gas

The implementation of Natural Gas shows itself in two ways: through the introduction natural gas deliquification port and the introduction of natural gas turbines. The natural gas deliquification port must follow the guidelines of the proposal agreed to by the Federal Energy Regulatory Commission (FERC). The ports also must be able to withstand the historic temperatures and natural disasters the area sees.

2.2.2 Renewable Energy

Renewable Energy in Puerto Rico has been implemented and proven successful. This proposal focuses on the introduction of additional solar farms on the country's southern coasts. These solar panels must be compliant with IEEE and safety codes and abide by contractual agreements as set forth by PREPA. Generally, Puerto Rico receives around 14 hours of daylight each day, or around 2829 hours per year. After contacting AES, it was deemed even on the days with the lowest solar irradiance readings in all of their plant's life, they still receive enough solar energy to produce electricity. Therefore, these panels need to be at a place that allows them to collect sunlight as well as be maintained and be in a location that benefits the surrounding public.

2.2.3 Energy Storage

Lithium Ion Batteries must be able to withstand the temperature swings and natural disasters with proper upkeep. They also must fall under reasonable budgetary means.

2.2.4 Cost Issue

Puerto Rico currently provides free power to all 78 of its municipalities, as well as many government-owned enterprises and even some for-profit businesses.(Williams Walsh, Mary , 2002) Along with that, the current electric utility rates are nearly $0.10/kilowatt-hour below the Caribbean regional average.(Energy Snapshot: Puerto Rico) These facts combined lead to the one main requirement of our plan: generate profit. This plan must propose a plan that in the long-term cost outlines generates a positive monetary amount for the currently bankrupt PREPA. This plan is also required to provide a cost breakdown of previously lost profits due to lack of maintenance, blackouts, and other happenings to provide background information on the money saved along with the money generated.

2.3 Constraints Considerations

The political and contractual aspects of the project will not be considered during this project and we will instead be supplying a concept of a better energy system for Puerto Rico.

There are also other constraints that are obvious such as the fact that most the work that we will be doing is mostly theoretical research. We are not able to go to Puerto Rico to witness what is happening there ourselves. However, we are able to contact a few power companies in Puerto Rico such as the Puerto Rico Electric Power Authority (PREPA), which is in charge of most of the islands electrical needs and AES, a private company with power technology on the island.

Another major constraint that can affect the outcome of the project is that when creating this power grid, we are mainly focusing on the theoretical side of the project. We can do our research and theoretically be able to create it as well as we can, but in the end, we won't be able to ensure that these projects will work physically.

The other constraint that might be a problematic issue when developing this power grid is that since we are using renewable energy such as solar energy and wind energy, the intensity of the sun that Puerto Rico is supplied with can really affect how the power grid will work. For example, research must be done to understand whether there are weeks where Puerto Rico does not get any sun and is facing cloudy days. This factor could really set us back because since the sun is something that we can't control, we can only look at the insulation data as reference.

2.4 Existing Hardware and Literature

2.4.1 Natural Gas Port

Puerto Rico has no natural gas reserves, so the country relies solely on imports to utilize this effective resource. On average, Puerto Rico imports 55 billion cubic feet of natural gas each year, mainly from Trinidad and Tobago. Furthermore, the only sector that uses natural gas is electric generation, and PREPA has plans in place to "add more natural-gas fired generating capability". (Puerto Rico Territory Energy Profile , 2017) Currently, of the 5.37GW of generation plants in Puerto Rico, only one 510 MW plant owned by Gas Natural Fenosa located in Peñuelas is fueled solely by natural gas. "Nearly all natural gas is imported as liquified natural gas (LNG) through the Peñuelas terminal and regasification facility at Guayanilla Bay on the southwestern coast." (Puerto Rico Territory Energy Profile , 2017) There has been a discussion of creating a pipeline to distribute this oil from the south coast to the north coast, but due to the mountainous region dividing the nation, the plan was discontinued, so currently a truck-loading facility allows the natural gas to be transported.(Puerto Rico Territory Energy Profile , 2017)

There has also been discussion of constructing a floating natural gas deliquification plant. Approved by the U.S. Federal Energy Regulatory Commission (FERC) in 2015, the plant would be "four miles offshore from the Aguirre generating station on the southern coast". (Puerto Rico Territory Energy Profile , 2017)

2.4.2 Renewable Energy

Puerto Rico has very few natural resources, leading to many imports of combustible fuel to generate electricity. However, renewable energy, specifically wind and solar energy, provide another source of electricity the country can utilize. It is true that Puerto Rico also has some other kinds of renewable energy like hydro power, biomass, the hydro power has already been utilized as indicated in DOE. (Energy Resilience Solutions for the Puerto Rico Grid, 2018)100MW capacity has already been installed for 120 MW potential hydro power. The kinds such as biomass requires a lot of technology industry chain to process the constant power generation which is still not feasible for puerto rico given the finance situation right now. And for the other type they share a really small amount compares to the solar and wind portion in electricity generation so they are not as imminent as solar and wind.

There are also several privately-owned solar farms on the island, including the AES Ilumina, Oriana Solar Farm, Salinas Solar Park, San Fermin Solar Farm, and Windmar Ponce.

- AES Ilumina is located in Guayama (24 MW)
- Oriana Solar Farm is located in Isabela (45MW)
- Salinas Solar Park is located in Salinas with (16 MW)
- San Fermin Solar Farm is located in Loiza with (26 MW)
- Windmar Ponce is located in San Juan with (14.2 MW)

Map of Solar Farms in Puerto Rico

Distributed solar has also been introduced. There are previous solar panels that are being implemented in Puerto Rico by Tesla. The solar panels that are implemented are set as supply storages in case of another outage of electricity. This was implemented after the absence of electricity from Hurricane Maria, and Hurricane Irma. This, paired with Tesla Powerwall stations, has been implemented to power dozens of homes.("Tesla solar power arrives in Puerto Rico", 2017)

After the event of Hurricane Maria, there are a lot of other companies that are trying to implement a better power grid for the island and hopefully work itself towards solar and wind energy. It has first been implemented to a children's hospital in San Juan, Hospital del Nino.

There are also existing wind farms on the island. The Punta Lima and Santa Isabel wind farms generate 26 and 100MW, respectively.

Punta Lima wind farm starts operating at 2012/10 and is located on the east side of the coast. The total cost for the project is 82 million.

Santa Isabel wind farm starts operating at 2011/9 and is located on the south side of the coast. The total cost for the project is 215 million.

2.4.3 Gas Turbines

Gas turbines are meant to be implemented into the power grid at the natural gas deliquification ports where they can generate energy through this. The natural gases will act as a backup or will co-supply power to the island. One of the major companies that are working on gas turbines is Siemens. Siemens is one of the leaders in gas turbines that has been implemented throughout the world.

The gas turbines that has been introduced to us by Siemens are Heavy-Duty, Industrial and Aeroderivative Turbines. Each turbines is used for unique purposes however, the one that we will focus on when implementing the power grid is the Heavy-Duty Turbines. These turbines act as cogenerators to other power generations which in our case would be the solar and wind energy.

The power that is supplied by these gas turbines range in various values and the cost of these gas turbines are up to 2 to 3 million. Siemens created a complete data overview of the different values of power output that their power grid can supply.

Currently there are a few stations of steam turbines, combustion turbines and many different turbines located in Puerto Rico for the use of petroleum. However, since we are avoiding the use of petroleum in our design for electricity, we would like to replace those with the gas turbines. These combined-cycle power plants can be implemented into the 510 MW combined cycle power plant for the natural gas which will increase the efficiency of the normal gas turbines by 61% by Siemens.

2.4.4 Interconnecting Microgrids

The microgrids are slowly being implemented by numerous groups of people due to how cost effective and improving the safety of power grids and improve grid performance. There are a few places that have already implemented and most of these implementations are done by Berkeley Lab and their microgrids. For example, the use of a microgrid was implemented in New York University. They have moved from an oil based power generation to natural gas combined heat power generation. From this they were able to provide twice as much power capacity compared to their previous power generation. The grid is connected to the Con Edison distribution grid and can get power from their when that grid has more power generating compared to the university. However, once Hurricane Sandy hit, the university was able to provide constant power to the campus and functions islanded to provide the required energy. There are also many different examples all over the world that Berkeley Lab have worked on.

This can eliminate the fact of having to depend on one single power plant/source to supply enough energy. This works as many smaller power sources to help supply energy. The works of this microgrid is focused by the Berkeley Lab which is trying to spread the use of microgrids around the world.

2.5 Proposed Design

This proposed design encompasess several main components: generation, transmission, microgrid implementation, renewable energy, energy storage, and economics and policies. During the design process, each decision was weighed in terms of feasibility and budgetary constraints, as well as resilience and reliability and storm hardening options.

2.5.1 Generation

Although the majority of the population of Puerto Rico lives on the north coast, the sole natural gas power plants are located on the south coast, far from the end consumer of electricity. Since pipelines proposals from the south to north have failed (Puerto Rico Territory Energy Profile, 2017), We instead propose the construction of a new natural gas port in the northeast area of the island with a natural gas pipeline connecting two generating facilities in San Juan.

Roosevelt Roads is a required naval base of over 3,000 square meters of available space for a new LNG regasification terminal. This area already has an installed port and ample space, so construction of a port and facility is very feasible. The existing regasification facility in Punta Guayanilla, Peñuelas consists of a regasification terminal with a 160,00m^3 storage tank with a capacity of 1.2 mtpa, 0.17 bcfd, which supplies natural gas to two facilities, the natural gas and heavy oil fuel-fired Costa Sur Generation Plant and privately owned natural gas-fueled EcoElectrica Generation Plant. We propose transitioning two main generating facilities located near San Juan - Palo Seco Generation Plant (602 MW) and San Juan Generation (400MW) - to natural gas fired with the introduction of this regasification terminal combined with a pipeline to the plants.

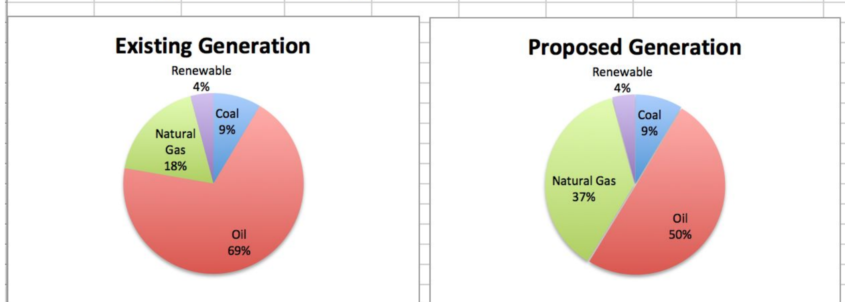
The proposed pipeline would span from Roosevelt Roads to the San Juan Generating Plant and Palo Seco Generation Plant would be approximately 40 miles long. To ease the permitting process, the pipeline would avoid the restricted El Yunque National Forest, which would save only 2-3 miles of pipeline installation. This cost savings would be outweighed by the extensive tree removal and right-of way maintenance that would be required through the park. The spread of San Juan extends approximately 15 miles from the San Juan Generation Plant, which would require the pipeline to be underground. However, after out of the city, the pipeline could be above ground to save in labor costs.

Proposed Pipeline Route from Roosevelt Roads

Labor costs are the #1 influencer in the cost of natural gas pipeline installation. (Smith, Christopher E. , 2016) Since the island has no skilled labor market for pipelines, outside will be brought in to install the pipeline. Labor costs can range from $2-3.6 million per mile in the United States, while materials, right of way, and miscellaneous costs combined equate to an average of $4.1 million per mile.(Smith, Christopher E. , 2016) Using these average rates, the pipeline would cost approximately $272 million to install.

COAL	OIL	NATURAL GAS	RENEWABLE
454	900	510	24
	247	450	45
	464		16
	592		27
	450		4.5
	602		26
	400		75

COAL	OIL	NATURAL GAS	RENEWABLE
454	900	510	24
	247	450	45
	464	400	16
	592	602	27
	450		4.5
			26
			75



Generation Breakdown (MW) With The Proposed Natural Gas Additions

It is also encouraged to increase coal storage at the 454 MW coal-fired generating facility and distributed coal turbines to hold coal for a 15 day blackout on the island should a natural disaster strike.

2.5.2 Transmission

As far as interconnectivity goes, the majority of research has shown very few stable connections between both towns and generation facilities. Our proposal includes adding transmission lines from town to town as well from multiple towns to each generation statement. Even before Maria, which made landfall in late September 2018, Puerto Rico's citizens often experienced blackouts, some widespread. For example, in 2016, the entire island experienced a 3-day total blackout after a fire in one of the plants. (Vives, Ruben, and Molly Hennessy-Fiske , 2017) Other statistics show Puerto Ricans suffer 4-5x more blackouts than the average American. (Vives, Ruben, and Molly Hennessy-Fiske , 2017) This can partially be attributed to the lack of interconnectivity and microgrids throughout the island. By adding an additional transmission loop near the population center San Juan, the transmission system will better be able to withstand line outages.

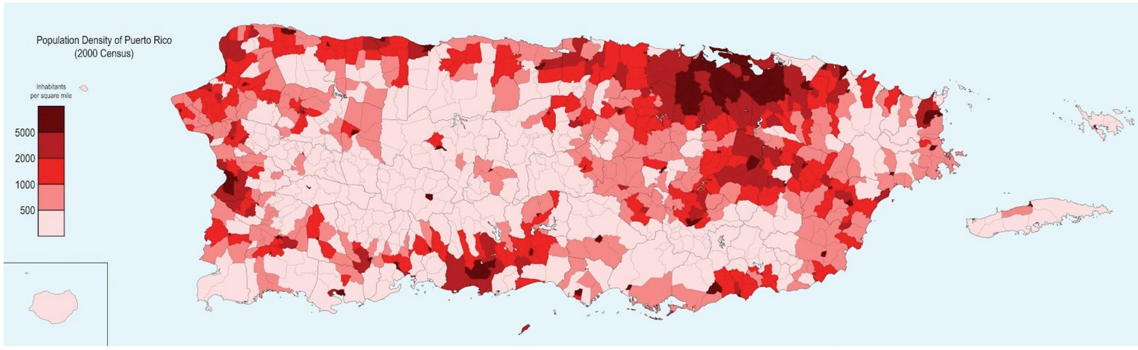
When repairing and replacing transmission towers, lattice structures withstood the hurricane much worse than their monopole counterparts. (Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico, 2017) Therefore, all hardware proposed for the rebuild will be based on the monopole design.

Lastly, the existing average yearly maintenance budget is approximately $17.1 million. (Fortieth Annual Report on the Electric Property of the Puerto Rico Electric Power Authority, 2013) However, the maintenance provided was not sufficient, causing many outages and downed lines long before the hurricanes hit. The narrow right-of-ways and lack of tree cutting will be fixed with an updated maintenance plan and budget.

2.5.3 Microgrid Design

As stated before, the microgrids are a very crucial part for designing our power grid because of how reliable the power grid will be for the whole island in case of another natural disaster or a powerful storm. Therefore, the design of the microgrid is very important not only for its reliability but also to ensure the power distribution is spread throughout the whole population of Puerto Rico, including the smaller mountainous rural areas and communities.

The initial utility in the design would be the power generation from different utilities including solar power, wind energy, and natural gas. Since we will be implementing the solar farms on the south coast of the island, and the population and critical loads are located around there, we will focus a few of the microgrids on that side of the island. These microgrids will then sparsely be connected to each other until it arrives on the northeast region of Puerto Rico. This area is the most highly dense population of the whole island. There are major cities such as San Juan, Bayamon, and Carolina that has a high number of population. One of those cities, San Juan, consists of 355,000 people which is a tenth of the whole islands population. On that region also is where the wind turbines are mostly located and the natural gas pipeline will be implemented. Therefore, the microgrids must focus a lot more on this region to provide enough and continuous power to the critical loads in those areas which are abundant.



Population Density Map

In total, among many different critical loads location in Puerto Rico, we have chosen a few of them which are located most convenient for our microgrids. All together we will implement 159 microgrids throughout the whole island.

The average microgrid that we want to implement the design will be spread among 15,000 people. Therefore, if we take San Juan for example, we will have to implement close to 24 microgrids in that area due to its critical loads and population. In San Juan, we will implement a gas turbine in that area because of the pipeline that will lead to the city for backup generation for the whole island. We also intend to implement solar panels on the roofs of the hospitals and houses to provide more energy and still have power connection from the south coast solar farm. The microgrid will also get power generation from the wind turbines connection throughout the island. These microgrids will then require a control center or plant for the turbines and also for the energy storages that are required to store the renewable energy that we are providing. These control centers must be implemented and maintained by proper authorities with proper qualifications.

For another example, we can take a small community like Maniti which consists of around 16,000 people will only have one microgrid implemented due to how small the city is. This microgrids will be similar to the one in San Juan. The microgrids are then spread throughout the whole island to provide constant power.

Solar Energy accompanied with solar microgrid

Solar Microgrid is a new technology implementation that we should step into for a more robust energy system. Comparing with traditional microgrids with limited storage, solar microgrids can be regarded as a small solar generation farm with grid. It can provide sustained solar energy itself and efficiently transmit electricity to residents inside of the grid. Also there are two parts we need to face when implementing this idea.

1. Setup microgrids around solar farm

As community microgrids are served for emergency power grid, the solar farm around them can provide more energy option accompanied with storage inside to increase the robustness of microgrid with its self-perpetuating process. Since we proposed for distributed solar system, it is ideal if we put solar-microgrids around them to reduce the overall cost as the largest cost for microgrid is the distributed energy resources.

2. Extra fee

Compare to traditional panel-converter-home electric system, connecting system to microgrids also requires extra cost for connection which may cause opposition to the plan. In 2013,Gram Power introduced the solar-microgrids to rural Rajasthan, India. Gram Power charged every family for one time $20 connection fee and $3/month for utility fee. Due to the lack of financial aid from government, people in developed country may hardly afford these extra costs and still wait for price to go down. To resolve this situation, privately owned company must afford the installation and configuration before they step into the market and give subsidy to low-income family.(Are solar Microgrids the future in the developing world, 10/3/2018)

2.5.4 Backup Turbines

When discussing about the implementation of the gas and coal turbines, it is important to take a few considerations into factor to ensure that the system functions properly and efficiently throughout the whole operation. These are some of the notable considerations that we must look into:

1. Different Types of Gas Turbines

   There are many different types of turbines that are offered by Siemens. There are the industrial gas turbines which is used for both industrial power generation and mechanical drive applications, the aeroderivative gas turbines which focuses on the use of aviation and the heavy-duty gas turbines that are used for large simple or combined cycle power plants. Since we are focusing on the combined power cycle in our design and we have to consider the robust of the turbines we decide to choose the heavy-duty turbines.

2. Heat Recovery

   Since we are working with gas turbines and the burning of the natural gasses in these gas turbines, it is crucial that we are able to help maintain the heat recovery of the whole plant. This is very important due to the fact that we want the system to be working optimally, therefore we will be using the heat recovery steam-generating system which will help filter out additional heat and maintain the performance of the gas turbines.

3. Control and Monitoring

   As we mentioned before, the heating of the gas turbines can truly be something that can negatively affect the performance and maintenance of the gas turbine. Therefore, their needs to be a control center for these turbines where there is always constant monitoring of the temperature of each of the gas turbines to ensure superheating or overheating happens. The control is also needed to ensure that sufficient power is generating for the intended grid continuously when it is required most. It will work as a control panel to understand when it will flow and when it should use its combined heat power to produce more power for the island.

2.5.5 Renewable Energy

2.5.5a - Solar Energy

Puerto Rico has abundant sunshine along the south coast with the radiation density about 2100 kwh/m^2 . Even San Juan has a slightly lower solar density it still has about 2000 kwh/m^2 per year. Since the 1.2GW solar farm in Abu Dhabi has about 2.42c/kwh rate delivered to the grid and Puerto Rico has only 5% less radiation than these cities, we can conclude that the average cost for Puerto Rico should be a little bit higher compares to those cities. Therefore, it is feasible to put solar farms near San Juan.The

Based on the approximation of Dubai, Chile and India, Puerto Rico's yearly solar radiation is about 1900-2000 kwh/m^2 with the unit cost of $3cents/kwh. The panel price in California in 2017 Dec was $3.23/watt (including installation cost and 30% federal credit), Puerto Rico should be similar. Since we are proposing 50MW solar in San Juan the total cost should therefore be $161.5million. Rooftop panel will generate electricity at about $13cents/kwh and is expected to generate 1900 kwh electricity with 1kw solar panel capacity, LCOE cost over 30 years at 5% interest rate.

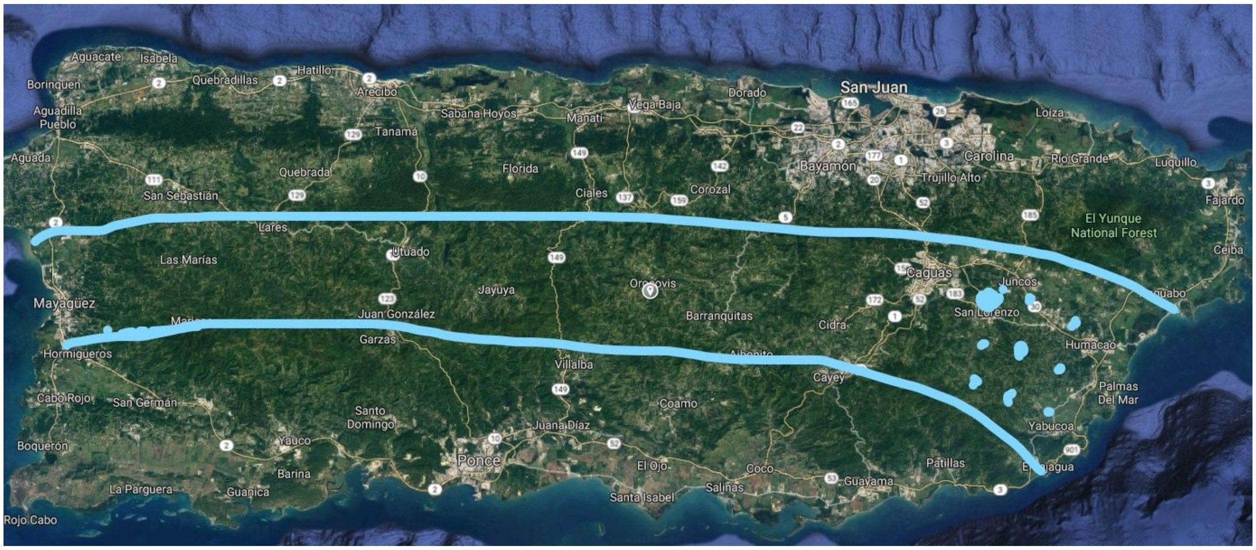
Given San Juan has 2000 kwh/m^2 radiation per year, a 10 m^2 solar can generate 4000 kwh power per year given the 20% efficiency. (solar resource maps and GIS data) At Ponce located at south coast the radiation is about 2100 kwh/m^2 per year. Therefore 10 m^2 solar here will generate 4200 kwh.We can make conclusion that there is approximately 200 kwh more of electricity generated for south coast compares to the north coast with the 10m^2 panel per year. Also, with the solar irradiance in San Juan, it takes about 0.1095 million square meter solar panel at an efficiency of 20% to generate the desired value. This value will provide 438 million kwh for a year in total.

It is not negligible that the solar economics has changed a lot during last three years in Chile, Dubai and India with the solar plant deliver electricity to the grid at about $3 cents/kwh. While San Juan does not have that much of solar radiation, we can make approximate the cost delivered to the grid should be around $5 cents/kwh in San Juan. And when we combine solar near San Juan with the natural gas pipeline, back up gas turbines, microgrids storage, we can make them to be a major part of the future of energy system in Puerto Rico.

2.4.5b - Wind Energy

Onshore Wind

Onshore wind is desired to be settled at high level position. Puerto Rico has the geography with its crest lay inside the middle of island. The highest mountain in Puerto Rico is Cerro de Punta at 1338 meters. Areas with 300-900 meters range are positioned inside the middle of island with high yearly average wind velocity about 18.9mph and the highest to be 22.4mph happened in summer. At winter these areas have an average speed of 20.8 which is the second largest during a year.(Puerto Rico and U.S. Virgin Islands - 50m Wind Power. 2007) All of them are speeds ranked with Class 5 above. Those speeds characterized that turbines will operate its maximum capacity at winter and summer given the operating speed for turbines at 8-30 mph.(Puerto Rico and U.S. Virgin Islands - 50m Wind Power. 2007)



Between lines are the region for 300-900m terrain, dots are the regions where we want to put the onshore wind farm

For our proposal we are planning to setup 30MW around these crests without the intersection of forest. The potential crest region lies in middle of island and most of the forest coverage is south on west side of island, north on east side of the island. Therefore, instead of only considering putting turbines around crest but should also keep away from the forest region to avoid possible damage of turbines.Therefore we propose to put wind turbines on the south east to the island.

The approximate cost for 30MW (30 turbines ranked at 1 MW each) is $90 million including installation. The separate cost for turbine is $1000/kw for installation and $2000/kw for gross turbine. The reason for 1MW is because large scale wind turbines without much of area distribution requires sustained strong wind power in local area. The crest has a much more wind power to meet the minimum requirement which means that turbines can operate efficiently and constantly throughout the whole year. A more large-scale turbine is preferred due to the wind characteristic around crest region.

Offshore Wind

San Juan has the most population in Puerto Rico and has abundant offshore wind speed compare to other coast. It is preferable to setup offshore wind turbines there to match electricity need. Also San Juan coast line has an average depth around 10-25m which is feasible for offshore-wind farm. (Wind Statistics for San Juan airport)Therefore, we propose a 50MW(25 turbines for 2 MW ranked) on the northside of San Juan coast. On the northside of San Juan coast, the average yearly wind speed is about 10.8mph which allows the turbines to operate normally throughout the whole year. The maximum power that those turbines can generate is from February to August at 12 mph for wind speed. Also we need to setup the wind turbines toward the wind direction coming into the coast to receive maximum wind power. From history data we can find that offshore wind is more likely to happen in southwest direction, therefore if we align those turbines toward southwest we should get the maximum power and the more distributed area they cover inside the path region that wind flows the more efficient these turbines will be.

Since Massachusetts is one of the two places that we can refer to for US offshore wind program, we can make approximation that Puerto Rico should be the similar case as Massachusetts. The cost for installed capacity is about $3030/kw(The cost and economic impact of New Jersey's Offshore Wind Initiative 6/2011) and the unit price for offshore wind delivered to the grid is $6 cents/kwh. We can estimate that for 50 MW in Puerto Rico the total cost is about 152 million.

2.5.6 Energy Storage

Energy storage, specifically for the renewable energy plants, will be a big factor in determining how much renewable energy is the 'right' amount to implement in terms of financial investment and reliability of power. For example, AES, who also runs some privately owned power generation facilities in Puerto Rico, has donated 6MW batteries to supplement the large-scale solar fields already installed. (Colthorpe, Andy , 2017) Other companies from around the world who are leaders in the energy storage company such as Tesla, Sonnen, and Tabuchi America have also donated time and money to the rebuild surrounding the grid. These donations help weigh down the cost of purchasing energy storage on its own, but purchasing enough energy storage to manage the installed renewable energy output is a large investment to make. AES has calculated that introducing 2.5GW of 10-hour battery storage could be sufficient, but other sources have argued the renewable power generation is too unreliable to ensure this amount would be sufficient.

A main focus of this plan to reiterate - this plan is NOT proposing a solely renewable energy-based design. While renewables are a great option, the lack of technology in the energy storage area combined with non-constant solar and wind resources and high initial and upkeep costs associated with renewable plants leaves traditional natural gas and other fossil fuels still a very stable and economically viable solution while the country works to rebuild its shattered power industry.

This semester we have decided to target various companies based on reviews and recommendations in order to obtain information about their rates and prices. In the first weeks we tried to contact the ABB company which is by many articles and magazines has been voted the leader in energy storage in the world. This first choice wasn't prosperous since ABB in their website and by other sources doesn't have much information about their batteries.

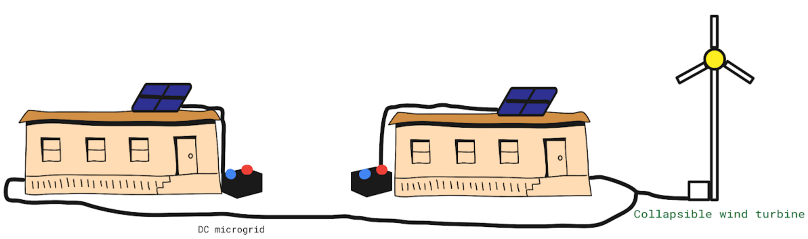
Our second choice was suggested by our mentor prof. Vikram Dalal. He first suggested us to look into the powerpack batteries that were installed in Australia this year that there was a lot of information on them. This Powerpack batteries are being used by a French company Neoen and this company has made 17 millions of the initial cost of installation which was 66 million dollars. Something that we find very productive and optimal for our proposal. After that we looked into their prices and rates

Model	Technology	Price (US$)[a]	Capacity (kWh)	Wh per US$	US$per kWh	Power
Powerwall 1	Lithium-ion	US$3,000	6.4	2.13	469	2 kW continuous
Powerwall 2	Lithium-ion	US$5,500 later U	13.5	2.46	437	7 kW peak; 5 kW continuous
Model	**Technology**	**Capacity (kWh)**	**Wh per US$**	**US$ per kWh**	**Operating temp.**	**Weight**
Powerpack 1	Lithium-ion	100	2.13	470	-	-
Powerpack 2	Lithium-ion	200	2.51	398	−22 to 122 °F (−30 to 50 °C)	3,575 lb (1,622 kg)

Although Tesla has all information available and we can project some cost with their rates, we found their rates also quite high for the island. So, proceed to continue our research until the last weeks of october when we were suggested of another company which has listed most of its information online. The BYD or Build Your Dreams company has the characteristics and types of implementation for each of their batteries which come in many sizes. BYD was our first choice ahead of Tesla for quite some time but after several attempts of contacting the company to get a quote. Due to the urgency of deliver data for our total cost and the proximity of the deadline to submit all our remaining information, we decided to keep Tesla as our provider of energy storage.

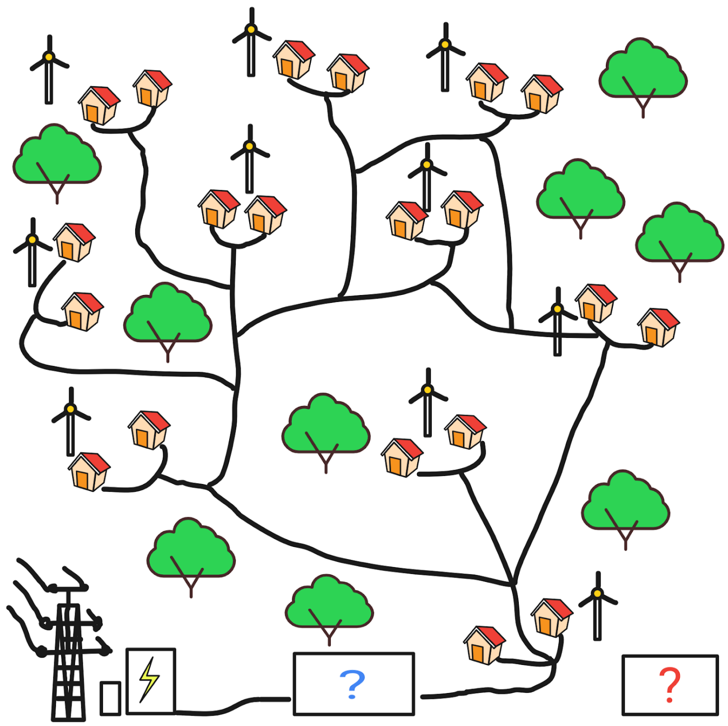
2.5.7 Rural Energy Solutions

For Rural zones of the island as we listed before we are proposing to get funding so that way we can make studies on how to implement DC microgrids on those places. As for the cost of these microgrids we can save considerable amount of money avoiding buying expensive inventors that are usually bought to convert to AC current, to finally deliver to loads that consume DC. Among the new implementations for these DC microgrids we plan to include smaller energy storage units or batteries. Most residents of these places don't have or use the same amount of devices that people on urban areas. So we plan to buy batteries that could be shared by two to three houses. These will feed the houses at moments the hybrid system isn't working. This way the system will be self sufficient to avoid future problems or terms of unproductivity, which is our main goal.



Coupled unit of the hybrid system

Cost that will be taken into consideration building these Microgrids is the cost of photovoltaic units, the “collapsible wind turbines”, the storage cost and the transmission line. So, far the only cost we still have to determine are the collapsible wind turbines and the batteries since it’s part of the proposed study.



?

This element is to signal an inversor from the upcoming AC power from the transmission lines from the main grid (bigger) that can be used to power the town in case of shortage or blackout.

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This would be a storage place for in case of disasters to safeguard the collapsible wind t

2.2.7 Economics and Policies

Economically, there are a few ideas being considered to better suit growth in the electric utility industry. Currently, Puerto Rico’s utility rates are around $0.24/kilowatt-hour, nearly $0.10/kilowatt-hour below the Caribbean regional average.(Energy Snapshot: Puerto Rico) However, a further cost reduction for the residential sector ($0.21/kWh) and industrial sector ($0.19/kWh)(Puerto Rico Territory Energy Profile , 2017) falls further below the average, pushing PREPA’s already enormous deficit even higher. Therefore, we propose raising the cost of electricity for each sector by 4 c/kWh to closer match Carribean averages and allow funding for the PREPA overhaul. However, we understand these prices are much higher than the continental

United States, and in the near future recommend re-evaluating pricing to bring it closer to the 12 c/kWh average in the United States.

Another factor in this ever-growing $9 billion debt is PREPA's gift if free power to "all 78 of Puerto Rico's municipalities, many government-owned enterprises, and even to some for-profit businesses".(Williams Walsh, Mary , 2002) This economic model has not been assessed since 1958, and many residents fear the repeal of this free power plan even though the plan does not directly benefit them. One main concern is that to pay for the energy, the citizens will have to increase property taxes or other spendings, an already touchy topic following an increased sales tax increase from 7 percent to 11 percent.(Williams Walsh, Mary, 2002)

First, the free power bill will be repealed. Free power is wasteful, and a large reason PREPA is in debt.

One solution we've considered is creating a subsidy plan for the current critical loads receiving power. The idea behind this proposal is the government would provide a monthly stipend to cover the electricity for the month. This stipend would be calculated based on current power usage and factor in wastefulness, so the stipend would be a fair and reasonable amount if electricity is used responsibly. Not only does this solution ease our the free power plan versus implementing a full payment plan right away, it also cultivates room to emphasize conscious energy use.

Another economic factor to take into consideration is focused solely on PREPA. Due to "Frequent turnover in management and leadership, which has long failed to prioritize grid maintenance"(Brown Nick , 2017) , there were many problems such as downed power lines and blackouts for months before Maria demolished nearly 80% of the current transmission and distribution system. Other factors play into this, including a tropical climate, but the root cause still remains at the lack of focus on maintenance from past PREPA leadership. By proposing that maintenance be treated with a higher regard and increasing the maintenance budget from $17.1 million/year to up to $50 million/year, the threat of seeing such a large percentage of the island's lines wiped out could be much smaller.

Several policies will also have to be adapted and edited to allow for maintenance and upkeep of the redesigned grid. First, the transmission right-of-ways will need to be widened to the world standard of approximately 30-45 meters. This will require extensive tree removal. However, by requiring a no net tree loss cutting policy, a new tree will be planted for each tree removed.

Several policies regarding rooftop solar will also be altered, allowing for the installation of large-scale rooftop solar in San Juan.

Lastly, we encourage signing coal and natural gas contracts while prices are low to allow for long-term savings

2.5.8 Budget

The table below shows the capital investments required for this plan.

Title	Cost (millions)	Details
Generation - Misc. Upgrades	$1,700	Storm Hardening, Facility Repairs
Generation - Natural Gas Generation	$2,600	Dual-Fired F-Class at Palo Seco and San Juan
Generation - Natural Gas Pipeline	$272	40 mile pipeline at U.S.average pricing including installation, labor, right of way, and miscellaneous expenditures
Generation - Natural Gas Regasification	$8,000	Repurposed LNG Floating Regasification and Storage Unit
Transmission - Misc. Upgrades	$7,050	Transmission infrastructure upgrades, substation upgrades, storm hardening, transmission additions
Renewable Energy - Solar	$161	50 MW solar investment and installation
Renewable Energy - Onshore Wind	$90	30 MW of onshore wind investment and installation
Renewable Energy - Offshore Wind	$152	50 MW offshore wind investment and installation
Renewable Energy - Energy Storage	$141	Lithium Ion batteries at $209/kWh
Total	$20,166	

2.6 Safety Considerations

It is assumed all hired contract and work will abide by the relevant standards of their trade and work with the relevant offices to ensure risk management.

2.7 Test Plan

For the test plan of the project, we have a major issue when designing this power grid. The issue is that we aren't able to go to Puerto Rico ourselves. Therefore, we have to test them using the softwares that are available as accurate as possible.

As mentioned before, there are a few softwares that we want to consider which does not require proper training to be able to use it. One of the examples is the Gridlab-D. This software will allow us to understand how effective a component will be in a certain area. There are many different utilities included in this online program. There are utilities such as solar, energy storage, voltage control and demand response. We will take solar for an example for the testing of its efficiency and understanding more of how the Gridlab-D program works. From this and inserting all the relevant information based on the utilities specifications that we intend to use, we can have a small summary of the few features that it will provide based on our design.

As we can see we can get a brief summary of the utility specifications that we provide such as the total energy from solar panels and the total energy consumed at the substations. However, this is only a tool for estimation for our design because this program only has two different climate regions and that is Seattle, WA and Bakersfield, CA.

Even though we aren't able to use the other tools given such as the OpenDSS, MDT and the DER-CAM, by contacting the appropriate authorities they can help with using these tool which two of them would be very beneficial to us. One of the design tools that is very useful would be the Microgrid Design Toolkit (MDT) which can help create a base design of the our microgrid. This tool can help design what we want in our microgrid with each utilities and power information and cost information involved. However, this would only be the base concept and would require to more information to ensure the reliability of the design instead of only the feasibility.

DER-CAM is the other design tool that can help understand how effective and feasible the design can be. However, this tool is implemented by Berkeley Lab Microgrids which they have used for many different locations in the world. They consider our design and see which method or direction our design should go to make sure that it is at its most efficient.

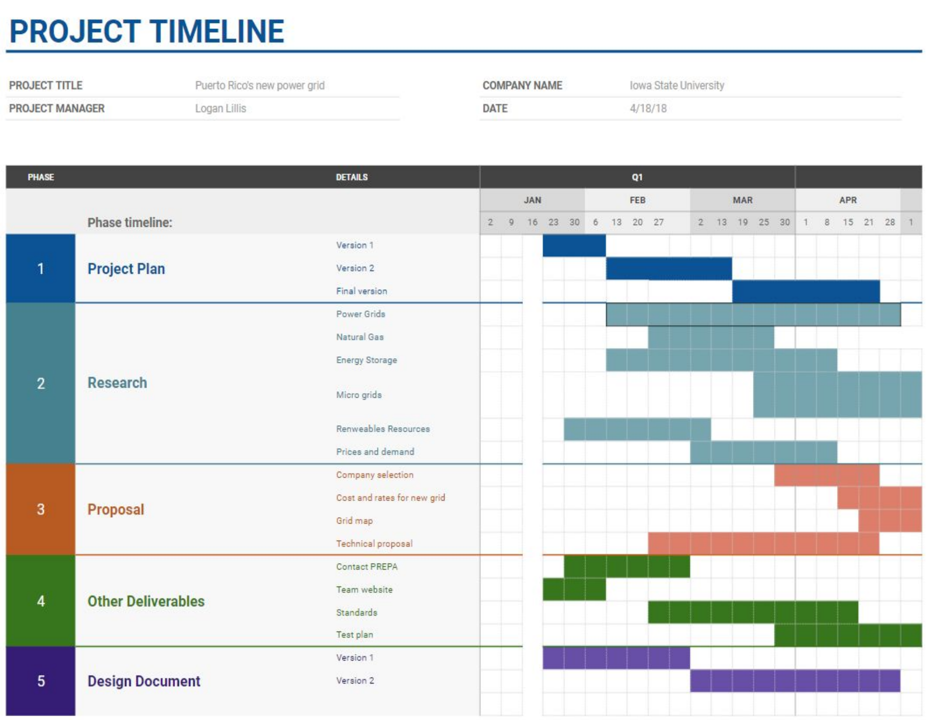
3 Project Timeline, Estimated Resources, and Challenges

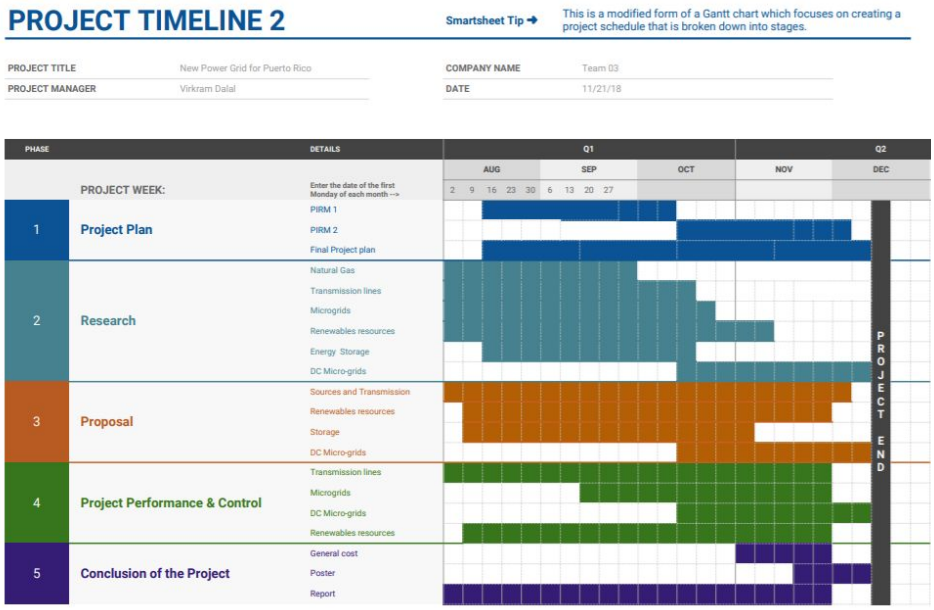
3.1 Project Timeline

Our project timeline consists on five primary phases to complete in our project. To be more precise this are the main components of our project for this semester. In our first timeline we delimited each task with different colors pointing the responsible of each one. In this timeline we will face each task as a team regardless of the amount of time or dedication that any teammate puts into the project with respect to others. We took this decision since it will help us to balance and coordinate the information, plus will help us more as a team. Each different phase of this project is correlated and we might be working in more than one at a time.

Documentation is a really big past of this first semester for our project, due to its importance, among the phases we pointed the duration and deadlines for the project plan and the design documentation versions. Research is our main activity in this first semester, on it we included each task petitioned by professor Dalal or those we felt relevant to our timeline. Then, proposal and other deliverables are the extra details extra to our documentation but no less important.

Those task that pass the final date of the semester finals or that “touch the black line” are going to be taken over again during the fall semester.





For the second part of the semester we implemented a different plan and with it a new timeline to fit our derivables. Important parts of our new timeline were the PRIM presentations which gave us new perspectives every time we assisted to them. Also different from last semester we have the new components of our research like DC Microgrids and Transmission lines. This timeline was very important in the complexion of our report and our proposal since it was vital to decide cost and what policies our companies adopt, due to the time restriction. Setting up a due time also helped us to maintain certain synchronization which is fundamental to set up a general cost.

3.2 Feasibility Assessment

After researching the background of Puerto Rico and its electric utility history, we found ourselves with the problem of deciding whether to redesign the whole grid of the country of Puerto Rico or to take only the critical zones affected by the hurricane.

After meeting with our client, we set our goal as creating an economic and technical redesign of the Puerto Rican power grid. Currently, the main obstacle preventing us from reaching our goal is finding reliable and in-depth information on the power grid. Also, our knowledge in power and geographic position of Iowa don't fully prepare us for taking coastal zones nor elevated zones (Mountains). Its sure that we must also design a grid capable of facing upcoming natural disasters on the future, because it will be pointless to build any new power grid and let the country equally exposed and in deeper poverty.

It is imperative to understand about management of power grids in general, and the old system of Puerto Rico. Find how many power plants the country has and where are those located. What alternatives for energy consumption the country has. What are the logistics of this biorenewables resources. In the case of Solar and Wind energy we must find parts of the country with more solar incidence and more wind flow. Finally to find among all these tasks we must determine and arrange the cost and price of electricity for the island itself and how will these prices accommodate to other sectors and institutions since previously the power in the island was totally free.

3.3 Personnel Effort Requirements

We expect to share most of the task and no individually assign problems due to the magnitude of this project and the logistics of our group. Logan Lillis, Communications and Reports Lead, keeps meeting minutes, writes weekly reports, communicates with outside parties, and has lead research on renewable energy, natural gas deliquification ports, generation, and the economic proposal. In semester one and lead generation, transmission, and natural gas research in semester two. Ricardo Rodriguez-Menas, Webmaster and Project Plan Lead, created and updates the project timeline and heads research on standards, compliance, and energy storage. Heiqal Zamri, Test Engineer Lead, is responsible for the structure and implementation of the test plan as well as research on natural gas turbines and natural gas imports, as well as research on renewable energy and microgrids. Pinjia Zhang joined semester two and was named the renewables energy lead.

3.4 Financial Requirements

Specifically for our team, there are no costs associated with the designing or proposal of this redesign. However, we require the proposal's budget to be reasonable and beneficial to Puerto Rico and their economy.

4 Closure Materials

4.1 Conclusion

In conclusion, this proposed plan will present a more reliable power solution for Puerto Rico in the form of economic and physical redesign of the current utility structure. By presenting data relating to the current grid and generation compared to data associated with the addition of physical grid and generation changes listed, we aim to prove a more reliable power grid for Puerto Rico is both feasible and a more sustainable financial option for the country.

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