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The Transition to a Renewable Energy Electric Grid in the Caribbean Island Nation of Antigua and Barbuda

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Abstract

The present study outlines the development and implementation of a computer model for Antigua and Barbuda's national electricity system, a dual-island nation in the Caribbean. The primary objective of this research is to investigate the cost-effective integration of renewable energy sources, including solar photovoltaics (PV), wind, and in the most novel contribution to the study, concentrating solar power (CSP). In addition to these technologies, the study explores the potential of battery and hydrogen energy storage to facilitate the transition towards 100% renewable electricity generation and the reduction of carbon emissions. This thesis is not solely a theoretical endeavor; it also identifies the practical aspects of concentrating solar power (CSP) by investigating its mechanical and operational procedures. Furthermore, the study encompasses a reflection on real-world experiences gained during an internship at Antigua and Barbuda's Department of Environment through the ETHOS center. This exposure provided insights into the local context and challenges, expanding the dimensions of the research. The motivation behind this investigation stems from the fact that many Caribbean nations heavily rely on diesel or heavy fuel oil for their grid electricity generation. Antigua and Barbuda currently generates 93% of its electricity from diesel-fueled generators. The nation has set goals of achieving net-zero status by 2040 and 86% renewable energy generation in the electricity sector by 2030, despite the absence of hydroelectric or geothermal resources. The study employs an assessment of the levelized cost of electricity (LCOE) for systems that combine various energy technologies and storage options to identify an economically optimal system. The analysis also considers factors like land use and job creation. The results indicate that 100% renewable electricity systems are feasible and more cost-effective than the current power infrastructure. This study underscores that there is no single defined path to achieve a 100% renewable energy grid; instead, it offers several viable options for the nation's sustainable energy future.

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University *of* Dayton

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1 Background

The nation of Antigua and Barbuda is a small dual-island nation located in the Caribbean Ocean. The nation is a part of a string of islands in the Caribbean known as the Lesser Antilles [1]. It is located East of St. Kitts and Nevis and North of Guadeloupe. The island of Antigua holds a majority of the population, while the island of Barbuda is located Northeast of Antigua [2], [3]. The islands are comparable in land area with the island of Antigua having an area of 281 km^2 and the island of Barbuda having an area of 161km^2. The nation's capital is St. John's, located on the Northwest part of the island of Antigua. The nation also has a dependent island, called Redonda, located Southwest of the Island in between Montserrat and St. Kitts and Nevis [4].

Figure 1: Map of Antigua and Barbuda. Source: [3]

The nation has a population of around 101,000 people. Of which, a majority are of African descent. The people of Antigua speak mostly English, as it is its official language. The majority of citizens here practice a Christian faith. The median age of citizens in this nation is 32 years old.

[1]Based on IRENA [37] but with ~35% EVs by 2035, a somewhat more conservative estimate on total fleet penetration than used in Ref. [37].

Around 24% of the population lives in an urban area, which is largely located in the capital of St. John's. The economy of Antigua and Barbuda is largely reliant on tourism and utilizing the captivating beaches and land they have here [4]. With a total land area of 443 km^2 between the islands, the land is taken up by around 21% agricultural land, 19% forest, and various uses including cities, volcanic areas, and more [5].

Antigua and Barbuda traces its roots European roots to the early 17th century when English settlers colonized the island of Antigua in 1632. The colonization of Barbuda followed in 1678 [6]. Before European contact, these lands were inhabited by indigenous groups, including the Taino and the Kalinago, formerly known as the Arawak and Carib peoples, respectively [7]. These original inhabitants were groups that lived particularly in the Lesser Antilles in the Caribbean region.

After colonization, the islands were initially utilized for the cultivation of tobacco, but it soon became evident that sugar was a profitable crop for the area. In 1674, the establishment of the first sugar plantation occurred, a crucial development that would shape the islands' economy for years to come. The profitability of the sugar industry hinged on the labor of enslaved individuals who were brought to Antigua and Barbuda. The cultivation and processing of sugar were labor-intensive, and many slaves toiled on the numerous plantations scattered across the islands [8]. Betty's Hope, among others, stood out as a prominent plantation, with nearly 200 such establishments dotting the landscape.

Emancipation from slavery in 1834 marked a significant shift, but labor exploitation persisted as many former slaves continued to work on the plantations for hardly livable wages. In the mid-20th century, Antigua experienced a movement that would lead towards a goal of self-governance. In 1958, the nation joined the West Indies Federation, a step toward autonomy and independence from the United Kingdom. However, this federation dissolved in 1962. Then, on February 27, 1967, the West Indies Act granted Antigua full self-governance in all internal affairs, a critical milestone on the path to sovereignty. Independence discussions in the 1970s were complex, particularly due to the unique relationship with Barbuda, which was a dependency of Antigua. Barbuda's economic challenges and desire for autonomy fueled debates. On November 1, 1981, Antigua and Barbuda finally achieved independence as a dual-island nation [6].

Antigua and Barbuda now operates as a parliamentary democracy with a constitutional monarchy. Understanding the nation's political structure and key figures is essential for comprehending the regulatory environment that impacts the energy sector. Government policies and political decisions directly influence energy policy and investment.

1.1 Economy

The economy of Antigua and Barbuda predominantly revolves around tourism, but agriculture and services also play vital roles. Energy is a critical underpinning of these sectors, affecting the cost of living, business operations, and the competitiveness of the nation's industries. The nation is considered a high-income nation based on its Gross National Income (GNI) per capita [9]. The nation holds a GNI of around $20,000 per capita [10]. However, the nation faces large barriers in the cost of living in the nation. The cost of living is around $1,500 per month in Antigua. In comparison, the United States has a GNI of over $70,000 per capita with an approximate cost of living of around $2,300 per month [11]. In this respect, the GNI per capita in Antigua and Barbuda is less than 30% of the GNI per capita in the United States, but the monthly cost of living is only 35% lower than the cost of living in the United States. To demonstrate the significance of this further, the monthly GNI, which is effectively the average income per month, in Antigua and Barbuda is only $150 more than the monthly cost of living where the same relation in the United States is over $3,500.

Tourism accounts for a significant portion of the economy in Antigua, with small shares of agriculture and manufacturing as well. The nation was once part of the production of sugarcane, but now typically grows more fruits and vegetables such as citrus fruits, mangoes, and eggplants [4]. Although there is some agriculture here, it only accounts for around 1.8% of its GDP. Industry follows with around 20.8%, and the largest portion of services, comprising tourism, accounts for around 77.3% of the nation's GDP, with a majority rooting from St. John's city, seen in Figure 2 [12]. The nation's exports are nearly equal monetary value to its imports in any given year. One of the largest contributors to their imports is refined petroleum products for their energy production [5].

Figure 2: Heritage Quay in St. John's City, Antigua. Source: [12]

1.2 Energy Sector Overview

Currently, Antigua and Barbuda's energy sector primarily relies on imported fossil fuels, particularly diesel. However, there is growing recognition of the need for sustainable energy solutions. As seen all across the world, energy demand is increasing with rising populations and the increase of electrification of buildings, transport, and more. Understanding the drivers of energy demand, whether residential, commercial, or industrial, is crucial for addressing future energy needs.

Antigua and Barbuda has access to a limited number of variety of renewable resources, constrained to wind and solar-based energy technologies. Exploring the nation's potential to harness these resources provides insights into its energy sustainability efforts. Energy efficiency and conservation measures play a pivotal role in reducing energy costs and environmental impact. The energy sector in Antigua and Barbuda is further explored in chapter 3 of this thesis.

1.3 Climate Vulnerability

The environmental consequences of energy production and consumption cannot be ignored. Analyzing emissions, air quality, and climate change considerations in Antigua and Barbuda informs the nation's commitment to environmental sustainability. Antigua and Barbuda accounts for an insignificant portion of the global greenhouse gas emissions that have pushed the Earth to experience the effects of climate change. However, participation in international collaborations and partnerships can significantly influence its energy policies and projects to do its part in reducing climate change's impact and increasing its security as it threatens its people in many ways.

Antigua and Barbuda faces many difficulties in the wake of climate change. As stated in the nation's Nationally Determined Contribution, "Antigua and Barbuda currently experiences several climate drivers, including changes in precipitation, extreme events (e.g., hurricanes and droughts), increased sea surface temperatures, and sea-level rise" [2]. These climate drivers impact people, groups, and sectors across the island. The nation is currently developing local, sectoral, and national adaptation plans to identify the vulnerabilities and risks and develop a plan to combat these.

The nation faces clean water shortages and the changes in precipitation and temperature extremes have begun to and are expected to further negatively impact water storage in personal storage tanks and national reservoirs. These drivers and their impact on water scarcity will impact agriculture, personal water use, tourism, construction, and the health sector [2]. These changes will also impact the local ecosystem on land and in the water, which will in turn impact the fishing sector in the nation.

The impacts of rising sea levels can have significant impacts on some of the major income areas in the nation. This includes a significant threat to areas such as the capital of St. John's city. This city is where a majority of the population lives and a significant portion of the economy in the nation is based here. It is a city along the coast of the nation, so has a very low elevation, making it especially susceptible to rising sea levels. If the city were to be impacted by rising sea levels, tourism, imports, exports, and services would all be impacted [2].

Finally, with the increase in the severity of tropical storms and hurricanes, the nation will continue to have to rebuild and repair buildings, infrastructure, and tourist attractions. This would also put a significant block on tourism and would negatively impact their economy. Also, the cost of living would likely increase due to increased needs for repair and imports of food and equipment for the repairs and rebuilding.

2 Concentrating Solar Power Technical Analysis

Concentrated Solar Power (CSP) is a type of solar energy that utilizes thermal energy from the sun. This technology is unlike the more common solar energy technology of solar photovoltaics (PV). CSP concentrates the sunlight to a central point or tube while solar PV utilizes the photons from the sunlight that reaches the solar panels. CSP has gained increasing attention as a viable renewable energy technology worldwide due to its unique ability to provide large-scale energy storage capabilities. The technology is particularly promising for regions like Antigua and Barbuda, which benefit from abundant sunlight throughout the year and have not yet fully explored the potential of CSP. CSP systems, unlike solar photovoltaic (PV) installations, can store thermal energy for extended periods, making them a valuable asset for ensuring energy availability during both day and night, as well as periods of intermittent cloud cover [13]. It is particularly interesting for the nation as they do not have access to renewable resources that can be used in dispatchable technologies, which can be turned on and off as needed. The only renewable technologies that they have access to are solar and wind resources, which are variable resources in the more common technologies of solar PV and wind turbines.

Figure 3: CSP Parabolic Troughs

To provide context for the analysis of CSP in Antigua and Barbuda, it is important to examine successful CSP installations in other parts of the world. Spain has been at the forefront of CSP development, with notable plants such as the Gemasolar Thermosolar Plant and the Andasol Solar Power Station [14], [15]. These facilities demonstrate the technical feasibility and economic viability of CSP technology, showcasing the potential benefits that can be reaped from harnessing solar energy through concentrated solar power systems. Antigua and Barbuda shares common climate characteristics with the regions of Spain that utilize CSP [16].

In general, CSP technologies utilize a type of fluid that absorbs reflected and concentrated solar energy from the sun that reflects off mirrors. This energy is converted into electricity via turbines. However, CSP has three common variations of the technology that are utilized in differing scenarios. These variations include dish/engine systems, solar power towers, and parabolic troughs [13].

The dish systems are the best fit for small-scale plants that are located near the energy demand. They utilize a literal dish that reflects the sun into a central engine that produces electricity. The dish mirror is mounted on a structure that can follow the sun throughout the day to optimize its solar output. They typically are used for systems of power between 3 to 25 kilowatts, which is well below the needs for this analysis [17].

The next technology is the solar power tower. The power towers consist of a large field of mirrors that reflect to a single location, the tower. The receiver at the tower then converts all the concentrated solar power into electricity via a turbine. These plants can either use a heat-transfer fluid or molten salt, which is also common in thermal storage and is utilized with this and the next technology [18]. These systems are best suited in remote locations, especially deserts, where there is no contact as they concentrate extremely high temperatures and energy to the power towers. Thus, the technology is not best suited for Antigua and Barbuda as the islands are so small and do not have a large flat and suitable area to implement the mirrors and power tower.

The most suitable technology that is commonly used is the linear concentrator system. In specific, this variation utilizing parabolic troughs is the best fit for the region. This system consists of long rows of large mirrors that reflect the sunlight to a tube with the fluid. The systems also can utilize sun tracking to optimize the output. They can be paired with thermal storage and can either use linear Fresnel reflectors or parabolic troughs. The Fresnel reflectors are flat and concentrate the sun in one tube or a row of tubes above the reflectors. The parabolic troughs are exactly what they sound like. They are parabolic mirrors that each have a tube of fluid that is attached to the structure that will then be sent to the turbine to be turned into electricity. These systems vary in size over the world with many in Spain rated at 50 MW which is very realistic based on the demand in Antigua and Barbuda. They also have the option of being scaled larger or smaller with the added benefit of thermal storage [19].

2.1 Contrasting CSP with Solar PV

It is essential to differentiate between Concentrated Solar Power (CSP) and Solar Photovoltaic (PV) technologies. While both utilize solar energy, they do so through different means. CSP systems use mirrors to concentrate the energy from the sun onto a heat transfer fluid, generating thermal energy that drives electricity generation. In contrast, PV systems directly convert sunlight into electricity through semiconductor materials. CSP's unique ability to store thermal energy sets it apart for this analysis, enabling continuous electricity production even when sunlight is unavailable [20].

For solar technologies, there are three types of solar energy that must be considered. The types of solar resources are called the global horizontal irradiance, the diffuse horizontal irradiance, and the direct normal irradiance. The global horizontal irradiance, referred to as the “Ground-Reflected Solar Radiation” in the Excel files, is the solar irradiance that reflects off the earth or whatever buildings, trees, or infrastructure that is around the CSP system. This value is impacted by a value called the surface albedo. The albedo refers to the surface’s ability to reflect sunlight. Thus, surfaces like snow or white-colored buildings have a higher albedo than grass fields or concrete. The diffuse horizontal irradiance referred to as the "Diffuse Solar Radiation" in the Excel files, is the solar radiation that has been scattered or diffused from clouds or particles in the air that would disperse the solar radiation. Finally, the direct normal irradiance, referred to as the "Beam Solar Radiation" in the Excel files, is the solar radiation that directly reaches the CSP mirrors. This value is the largest and most significant factor in understanding the viability of solar energy technologies in an area [21].

Solar PV is a much more prominent technology than CSP, but CSP has the advantage of thermal storage. The way that each of the technologies can be modeled is very similar. However, a primary difference is that solar PV utilizes sunlight that reaches the panel from the ground horizontal irradiance, the diffuse horizontal irradiance, and the direct normal irradiance. Thus, when the electrical output is calculated, the sum of the ground horizontal irradiance, diffuse horizontal irradiance, and direct normal irradiance will be multiplied by the array area and solar panel efficiency, which is typically around 20%. CSP relies on the direct normal irradiance to collect energy. This is due to the fact that CSP concentrates the energy on mirrors, where ground horizontal irradiance and diffuse horizontal irradiance make negligible contributions when hitting the mirrors.

2.2 Mathematical Modeling and Equations in Excel

The research began with the mathematical modeling of the parabolic trough CSP technology tailored to the unique climate of Antigua and Barbuda. The development of these models requires a comprehensive understanding of the physical principles CSP systems undergo to produce electricity. Essential equations include those related to the concentration of sunlight, heat transfer, and the thermodynamic processes involved in converting solar energy into electricity. These equations form the basis for predicting CSP system performance and electricity generation capacity under a common year in the nation.

Accurate weather data is crucial for constructing reliable CSP models. The research utilizes historical weather data for Antigua and Barbuda, including solar radiation, temperature, and cloud cover patterns gathered from an open-access database called NASA POWER [22]. These data sets are essential for assessing the feasibility and efficiency of CSP systems within the local climate and environmental context.

To begin the calculation process, several data were needed to calculate the hourly output of a theoretical CSP plant in the nation. The first piece of information that was required was identifying a suitable spot for the plant to go because the latitude and longitude impact the solar output of the system. Then, three weather related data sets were needed to produce an hourly solar output for the theoretical plant. These datasets were the clearness index, solar radiation on horizontal, and air temperature. The clearness index can be defined as a metric used in the field of solar energy to quantify the atmospheric conditions and the amount of direct solar radiation that reaches the Earth's surface. Solar radiation on horizontal is a term, often referred to as global horizontal solar radiation, that measures the total solar energy that hits the horizontal surface of the Earth in that specific location. When this number is large, it signals that more solar resources can be utilized in energy production. Finally, the air temperature is simply the ambient temperature at the location.

The model was completed in Microsoft Excel, where these data and data defining various controllable factors including the setpoint of heat-transfer fluid, solar collector field size, and tracking capabilities were utilized. To gain the hourly output of the theoretical plant, calculating many angles of the sun and its relation to the CSP mirrors is required. The equations included calculating the solar altitude and azimuth angles, which are angles of the sun defining how far above the horizon and the deviance from due East, respectively. Then, an equation was needed to identify the optimal tilt angle of the array of panels based on these angles was utilized. Based on the tilt angle of the panels and the solar angles, the solar incidence angle was evaluated. The solar incidence angle is the angle between the sun and a line perpendicular to the Earth's surface. Thus, as the angle reaches zero, the concentration of solar energy is at its peak.

Once all these angles are calculated, the solar output can be found. This is done by several new equations that break down the global horizontal solar radiation. This value can be broken down into global horizontal irradiance, diffuse horizontal irradiance, and direct normal irradiance. Again, in the CSP modeling, only the direct normal irradiance can be accounted for due to the nature of the mirrors concentrating the solar radiation on the heat transfer fluid. However, when calculating the PV solar output, all three of these components will be summed because solar PV technology creates electricity from the photons in the solar resources that directly transforms the light into electricity.

In a CSP plant, the energy is captured and stored thermally, so the direct normal irradiation, in kW/m^2, is used in an equation that accounts for the total array area, air temperature, the thermal fluid inlet temperature, a modifier for the angle of incidence, and efficiency of conversion of energy into the fluid. Then, to calculate an electrical output for each hour, the thermal energy output can be multiplied by the Carnot efficiency and turbine efficiency, both near 50% for every hour. The turbine efficiency will be predefined by the turbine, but the Carnot efficiency will depend on the ambient temperature and setpoint temperature of the heat transfer fluid. This will result in the final electrical output of the CSP system and can be calculated for every hour in a year in kWh/h. The same steps are taken for calculating the solar output for solar PV except the direct normal irradiance, diffuse horizontal irradiance, and ground horizontal irradiance and are used in the same equations.

2.3 PyPSA Optimization Tool

The mathematical models employed in this research combine the Excel spreadsheet-based calculations with the capabilities of an open-source Python environment called PyPSA (Python for Power System Analysis) [23]. PyPSA is a tool that can be used to find a cost-optimal combination of energy generation technologies. It integrates various parameters, including energy demand, any energy technology that can be characterized by hourly production and costs associated with production or construction, and energy storage. PyPSA is a holistic approach that allows for a comprehensive analysis of energy generation, consumption, and storage. These analyses are all based on a defined timeframe, in this case, every hour for a sample year, with a total of 8,760 time intervals. Finally, it is required that there is a demand value for each time interval in the specific optimization.

PyPSA is capable of accounting for virtually any power generation. In general, there are four basic attributes for any power generation source. These attributes are the nominal capacity, the nameplate capacity of the generator, capital cost, the cost to build the generator, the marginal cost, the cost per unit of electricity produced, and the hourly generation profile. For example, any controllable, or commonly known as dispatchable, source of energy can be easily accounted for by having an associated capital and marginal cost, while being able to produce 100% of its rated capacity for every hour in the given timeframe. The Excel files previously described for solar PV and CSP hourly generation were required for the PyPSA optimization. This generation must be scaled between 0 and 1. Thus, each hour of the CSP output was divided by the largest single hourly output for the year. However, for the scaled output for solar PV, a different approach must be taken. A solar panel can only produce around 75% of its nameplate capacity. Thus, the approach to calculate the scaled output is based on a real solar panel, its area, and its rated capacity. The electricity generated from these generators can be stored in storage technologies that can be represented in the environment.

The storage aspects of the PyPSA environment are flexible as well. They also can have associated capital costs. The technologies are defined with a maximum storage capacity, which is the largest amount of energy in a specified unit of electricity, the storage technology can hold at any given time. These storage technologies can have links between the generators and the demand which can account for any additional costs of transforming the energy to electricity or some other form of energy to store, such as hydrogen, and efficiencies associated with the charging and discharging of the storage technology.

These different components can be set to specific values. For example, a fossil fuel based generator can be set to a specific nominal capacity that will remain unchanged in the optimization scenario. However, PyPSA is used to find the optimal mix of technologies that will minimize the cost of energy over the timeframe given. Thus, it is possible to put no restrictions on the technologies, but it is also possible to put maximum and minimum limits on each technology that the optimization will be restricted between. These limitations can be beneficial when analyzing renewable energy penetration or when considering reasonable limits or requirements based on a community's, region's, or nation's context in implementing specific technologies. These could consider policies, land restrictions, or specific goals. More information on the specific pieces that must be accounted for in this PyPSA optimization are described in the following chapter.

For optimization, PyPSA has several optimization methods. These methods include with Linopy, with Pyomo, and based on custom code. Linopy and Pyomo are predefined methods within the Python environment. They utilize their own equations to identify the optimal solution. In this case, the lowest cost for electricity for the given timeframe based on capital and marginal costs. PyPSA requires in its optimization that the demand for each timeframe is met, with no exceptions.

This environment has many other functionalities that were unused in the optimization for this study. These functionalities include greenhouse gas accounting and detailed electric grid considerations. Generators have the capability to account for greenhouse gases based on the hourly power generation for fossil fuel powered generators. PyPSA also has attributes that consider distribution and transmission of both AC and DC electricity. It also is capable of mapping plants on a map if the appropriate longitude and latitude are given with connections of the transmission and distribution lines connecting various technologies and demand areas.

3 Energies Publication

The following chapter is the main result of the present honors thesis. The primary quantitative results, methodology, and discussion of the opportunities of the nation of Antigua & Barbuda are present in this chapter. These results are an ideal scenario that minimizes the cost of electricity for a typical year in the nation. This section was published on the *Energies* journal, titled “The Transition to a Renewable Energy Electric Grid in the Caribbean Island Nation of Antigua and Barbuda” [24].

3.1 Introduction

Antigua and Barbuda is a small dual-island nation in the Caribbean, the most northeastern island of the Lesser Antilles **[1]**. Of the total population, 97% is on Antigua, although the islands are comparable in land area, with the island of Antigua having an area of 281km^2 and the island of Barbuda having an area of 161km^2 [25]. The tropical climate has very little variation throughout the year, with the median temperature in any month not falling below 25℃, based on measurements from the past 30 years [10]; Antigua receives around 2,782 hours of sunshine a year [26]. Key environmental issues for Antigua and Barbuda include water management, with minimal freshwater resources on the islands, with the impacts of deforestation from colonial sugar plantations allows rainfall to run off more quickly [5]. Susceptibility to tropical storms and hurricanes further exacerbates these environmental issues, leading to increasing efforts toward resilience and adaptation to climate change. One potential solution the nation has looked into for water purification is using wind power for desalination, which would require a significant additional amount of electricity [27] but would increase resilience.

Electricity generation in Antigua and Barbuda is nearly completely reliant on imported petroleum products. Diesel energy comprises 89% of the 87.45 MW of installed capacity for the nation [28]. The electricity production and distribution are operated by two companies: Antigua Power Company (APC) and Antigua Public Utilities Authorities (APUA) [29]. APC is the private company that owns the generating capacity, whereas APUA is the utility company that distributes the electricity and charges for its consumption. The companies work together very closely, as APC sells the electricity it produces to APUA to then sell to its customers. These plants, combined with other small backup generators that are owned by individuals and businesses, contribute to the nation emitting just under 200,000 metric tonnes of carbon dioxide per year from the electricity sector, and 650,000 metric tonnes total from the energy sector. The nation is hoping to reduce that number drastically as it sets a goal of reducing emissions in the energy sector [28].

Antigua and Barbuda's commitments to the Paris Agreement as outlined in their NDC include targets of becoming a net-zero nation by 2040 and having 86% renewable energy generation in the electricity sector by 2030. Additional targets to be achieved by 2030 identified explicitly in the NDC include having 100 MW of renewable energy capacity for the grid, targets to construct 20 MW of wind energy, 50 MW of renewable energy capacity owned by farmers who can sell to others, and 100 MW of renewable energy capacity owned by social investment entities such as non-governmental organizations, bus associations, or any other businesses registered as social investors. The NDC also identifies the need to establish a framework to achieve these goals by 2024. Finally, a specific goal relevant to the current work is that 30,000 homes, or 50% of pre-2020 homes, should have back-up renewable energy systems for at least 4–6 hours of energy. The solar resource for Antigua is approximately 6 $kWh/m^2/day$, and therefore, solar PV is a well-suited technology for this goal. In 2020, the residential sector in Antigua consumed 103 GWh of energy [28]. With the current total household count at 30,213, this implies an average of 3,400 kWh of energy consumed per household [30].

However, with increased consumption of electricity in homes and introduction of electric vehicles (EVs), which the nation aims to progress towards, it is likely the annual household consumption will increase. An average personally owned vehicle would require just over 1,750 kWh in a year [31], [32]. Combined, a household would require around 5,250 kWh per year. In Antigua, a solar panel can produce upwards of 1,500 kWh/kW_{peak} [33]. Thus, a 4 kW array of solar panels will produce about 6,000 kWh in a year. This will be larger than the required 5,250 kWh households from past data and EV introduction, which will give room for the electrification of homes. With the NDC target of 30,000 homes having solar PV systems, approximately 120 MW of rooftop solar PV will have to be installed to achieve this NDC target.

Recent legislation and policies including the National Energy Policy and Environmental Protection and Management Act [34] set out goals of reducing carbon emissions from the energy sector by 62% by 2027 and 90% by 2030 [34]. These and other policies cover the plans of protecting their local environments, implementing renewable energy into their energy system, ensuring affordable, equitable, and accessible energy to all, and developing standards for buildings and vehicles to increase their energy efficiency.

To achieve the goals of transitioning to renewable energy and reducing carbon emissions in the energy sector, it is necessary to understand which technologies would best fit the nation's renewable resources. With solar energy being a viable and abundant resource, both solar photovoltaics (solar PV) and concentrated solar power (CSP) are considered in this work, along with wind energy, which is also a part of the NDC targets [2]. These three sources, along with energy storage technologies (batteries and hydrogen) will be the most viable low-carbon and market ready options for power generation in the country based on the nations' renewable resources. CSP is a technology that has not been considered for the region, but we postulate that it is well suited based on its operational needs of high number of sun hours and direct solar incidence.

Geothermal energy and hydropower are two technologies that neighboring islands can potentially utilize, given the abundance of geothermal resources in parts of the Caribbean. However, Antigua and Barbuda (together with Barbados) do not have geothermal energy as an electricity generating option [35]. Hydropower is also not an available resource in Antigua and Barbuda, although some nearby nations have been able to take advantage of that resource.

3.2 Methodology

3.2.1 Electric Grid Simulation Model Description

PyPSA (Python Power System Analysis) is an open-source Python framework used to model energy systems [23]. In the case of Antigua, we have used PyPSA to investigate the cost-optimal mix of solar PV, wind, and CSP, together with energy storage, with the aim of achieving 100% renewable electricity and zero emission [2] in the timeframe of 2035-2040. In PyPSA, the system is configured with several components: buses, loads, generators, links, and stores. Each bus has generators (plants that produce electricity) and loads connected to it, as well as energy storage (stores); links connect buses to one another. There are four buses in this scenario, with one containing the load and all the generation technologies except CSP (Antigua), a separate bus, Antigua CSP, for all components of the CSP system, as well as a bus each for utility battery charging and discharging and for hydrogen generation and storage. A schematic of the process flow is shown in Figure 4.

For the Antigua bus, there is a load, Antigua Load, which contains the hourly electricity demand data for the country, with three generators: diesel power generation (Antigua Fuel Oil), wind-power (Antigua Wind), and solar PV (Antigua PV). Wind and solar PV can charge the Antigua battery storage or generate hydrogen if they produce more energy than the load in a given hourly interval since they are all linked to the Antigua bus. The Antigua CSP bus has a generator for the concentrating solar power (CSP) solar field and can charge the CSP Thermal Storage store since they are both under the same bus. Finally, any of the stores can meet the demand of the Antigua Load. When the load is larger than all the incoming power, the stores are able to meet the remaining loads. The links can take into account capital costs if used to represent, for example, an electrolyzer or a fuel cell or a turbine converting thermal energy to electricity in the CSP module. Process efficiencies associated with charging and discharging of the batteries and the conversion of electricity to hydrogen (electrolyzer) and then hydrogen back to electricity (fuel cell) are assigned to the links. Since there is no load for the Antigua CSP bus, the energy generated by the CSP solar field will either try to meet the Antigua Load through the link, CSP Turbine or charge the

CSP Thermal storage, with associated capital cost for the turbine and thermal storage having capital costs that are used as input to the optimization.

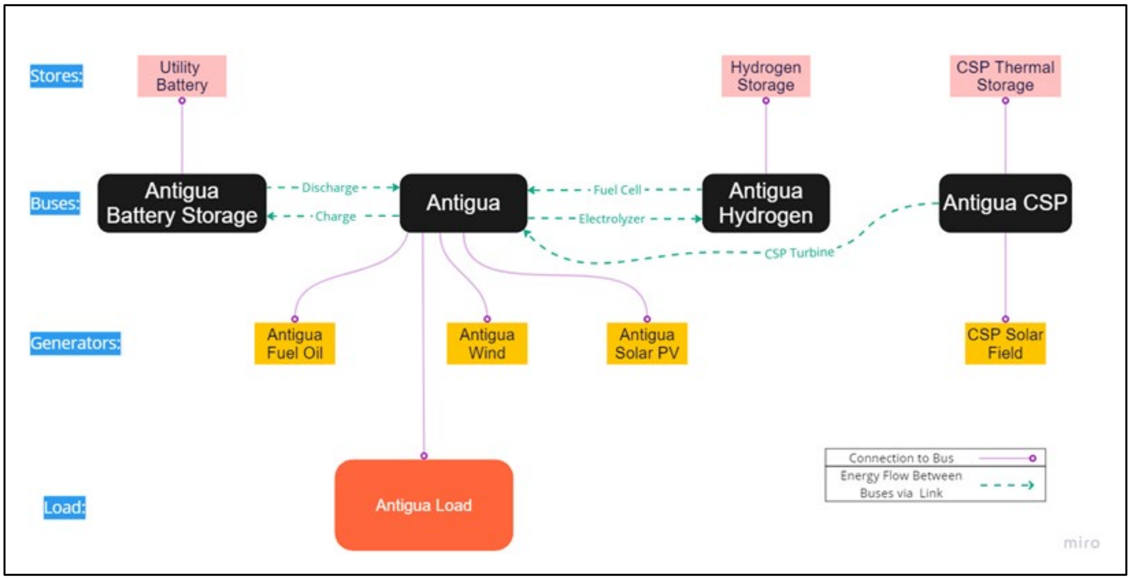

Figure 4: PyPSA Flow Diagram showing the main components of the modeled system. "Buses" represent the main centers of connectivity and are separated into a main system bus and three storage buses, each with a "Stores" technology. The "Generators" are generating technologies connected to buses. The "Load" represents the hourly demand for electricity during the year. "Links" represent efficiencies to store energy and/or the methods in which the energy is transferred between "Buses".

This model energy system presented here for Antigua can be easily modified to analyze other areas in the Caribbean, or other regions around the world by using the appropriately determined renewable energy resources, capital and marginal costs, along with the country electricity hourly demand profile.

3.2.2 Load Description

Load data used in the model is based on estimates of typical loads for Antigua, but hourly load data as needed for the model are not publicly available. Thus, a load model was used to represent the approximate load pattern for every hour of the year in Antigua, based on actual open-source hourly data for Martinique [36], which has been scaled to Antigua based on the total and peak demands that are publicly available [35]. Although the two countries differ greatly in population, load patterns are similar. To gain an estimation for the demand profile for the year 2035, the model was multiplied by a factor of 1.2 to account for both growing power demand of approximately 10% based on past trends and an estimated additional 10% load based on increased vehicle electrification [37][1]. Although based on [37], a slightly lower value for penetration of electric vehicles (EVs) of 35% by 2035 has been assumed for this model. This constant factor assumes that the load profile remains the same into the future, an assumption that may not hold under higher penetration of EVs and grid interactivity that are also included as targets in their NDC [2].

3.2.3 Generator Descriptions

The current electricity production system in Antigua is heavily reliant on heavy fuel oil generators. To address the NDC targets, we construct several model scenarios that do not allow for any fossil fuels, which implies large amounts of solar and wind energy, together with storage. For every scenario, hourly generation was needed to determine how the variable renewable energy sources, wind, solar PV, and CSP, will contribute to satisfying the demand for each hour of the year.

CSP is a technology that has not been used in the Caribbean, but Antigua and the Caribbean receive a lot of direct sunlight. Spain has many CSP plants in Alvarado, Majadas, and Orellana [38], which share similar climates, getting a similar amount of total sun hours in a year as Antigua [16]. Thus, it is logical to test if this technology will decrease costs of energy for Antigua. This technology

[1]Based on IRENA [37] but with ~35% EVs by 2035, a somewhat more conservative estimate on total fleet penetration than used in Ref. [37].

also has very long storage time in some plants such as the DEWA IV CSP-PV hybrid plant in Dubai that has 10 hours of storage for its trough CSP, so it can hold energy to distribute for the late peak demand that occurs most days in Antigua [39]. Utility batteries today are essentially held to 6 hours of storage at best but are estimated to reach up to around 10 hours of storage in the future [40]. However, CSP thermal storage has reached up to 14 hours in some plants, and research is being done to extend these times as well [41]. This combination of reasons motivates including CSP in this analysis and is specifically relevant for Antigua where there are no other dispatchable renewable energy resources to complement wind and solar PV.

An hourly output of each generator was needed for PyPSA modeling. The solar PV and solar CSP used hourly output for the systems using the NASA POWER database which has hourly data for various weather conditions from several years for Antigua [22]. A more detailed explanation of the hourly CSP output calculations can be found in Appendix D. Wind energy hourly generation estimates were taken from renewables.ninja reanalysis data for Antigua [33]. As input to PyPSA, each source is scaled to unity and can then be used to calculate the system output depending on the capacity installed. Worksheets used to determine CSP system properties are included in the Github repository referenced at the end of the manuscript.

3.2.4 Stores Descriptions

PyPSA has two types of storage methods available: (i) storage units based on fixed hours of storage and variable power, and (ii) stores with a fixed output power and variable number of hours of storage for each unit. The latter was used for this present study. Capital costs of the technologies in units of $US/MWh were provided as inputs. The amount of energy in the storage units at the first hour of the model was set to be equal to the energy stored in the last hour of the model for the optimization to avoid end effects of storage either having to be initially charged or to avoid seeking a solution in which all stored energy was discharged at the end of the modeling period. The model was constructed for an annual period, allowing annual cycling in a multi-year simulation.

Both utility-scale batteries and hydrogen were used as storage technologies in this study, in addition to thermal storage from CSP capacity. Utility-scale batteries were only given a limitation in two of the groupings of scenarios done in this analysis. That limit was set to 6 hours of storage for the scenario where all the renewable energy technologies considered in this study were included and 10 hours for sensitivity tests. This type of storage is compatible with wind and solar PV energy. The CSP thermal storage was given a limit of 24 hours for all the scenarios to reflect dual 12-hour storage tanks. Dual storage tanks are used in many CSP plants around the world [42]. The storage systems that are found in the results are effectively given not in terms of thermal storage but rather in terms of resulting electrical output. The thermal storage would be around three times as large as the results shown due to generation efficiency in converting thermal input to electrical output. This difference intrinsically takes into account the capital costs because the storage and generation capital costs defined in Table 1 and Table 2 are based on electrical output and electrical storage. Also, the thermal storage has a nonzero minimum that would need to be maintained, but for the purpose of this study, having a minimum of zero is suitable for the model. The charge and discharge efficiencies of the batteries were 95% (which results in 90.25% overall efficiency) [43], with efficiencies being implemented through the PyPSA links.

For energy storage and electricity production with hydrogen, the model included electrolysis, hydrogen storage, and fuel cells for converting hydrogen back to electricity. The efficiency of electricity to hydrogen through electrolysis is set at 75% and then the fuel cell turning the hydrogen back to electricity has an efficiency of 60% [44]. The electrolysis and fuel cell technologies will be characterized through the links connected to and from the hydrogen store, which takes into consideration each of these efficiencies and capital costs. Since hydrogen can be stored essentially indefinitely, the storage size can be much higher. The hydrogen storage was not given any limitations for that reason.

The CSP plant generates thermal energy that is then converted into useful electrical energy before reaching the grid. However, since the power generated from the "CSP Solar Field" generator has already taken this into account, the storage will be in terms of useful energy rather than in terms of thermal energy. All energy that is generated or stored in the CSP bus will be transferred to the load under the Antigua bus via the CSP Turbine link that has an associated cost.

3.2.5 Technology Economics

The following tables outline the capital costs of each type of technology. There is also a marginal operating cost, mainly fuel, associated with the diesel generator, which is included in Table 1. Costs for all technologies are estimates for the period of interest, in about 2035, and therefore necessarily very approximate. However, we consider these estimates to be conservative, as wind and PV systems have already achieved these cost levels in larger countries today. Capital costs for the stores are shown in Table 2.

Table 1: Generator and Link Capital Costs

Generator	Capital Cost ($/kW)	Marginal Cost ($/MWh)
Diesel [45]	1,800	1.70
Wind [46]	1,350	N/A
Solar PV [47]	880	N/A
Concentrating Solar Power Solar Field [48]	2,640	N/A
Concentrating Solar Power Turbine [48]	760	N/A
Hydrogen Electrolyser (Link) [44]	1,000	N/A
Hydrogen Fuel Cell (Link) [44]	500	N/A

Table 2: Store Capital Costs

Stores	Capital Cost ($/kWh)
Utility Battery [40]	143
CSP Thermal Storage [48]	50
Hydrogen Storage [44]	33.33

To interpret the results given from PyPSA, a levelized cost of electricity (LCOE) was calculated by dividing the total system capital costs, plus marginal costs, by the total yearly demand in MWh. Since the model is creating an energy system based on only one year of data, the capital costs of all technologies need to be modified to represent a real levelized cost of electricity. Thus, the capital cost values above were multiplied by a capital recovery factor (CRF) using a discount rate of 7%. Further details are described in Appendix B.

3.2.6 Limits on Technologies

A set of constraints were implemented in the model corresponding to minimum capacities in (renewable) technologies already installed, as well as maximum capacities as estimated from physical and technological limits. For example, wind energy was set to maximum values in increments of 25 MW to understand how the solar PV, CSP, and storage technologies would respond to the extra demand the wind was not covering. Although there is a published estimate of a potential of 400 MW of wind power capacity in Antigua and Barbuda [35], wind energy capacity of larger than about 50 MW appears unlikely given concerns about the tourism industry. Solar PV capacity was not given a limit as the results proved to be reasonable. With the inclusion of rooftop solar PV and the knowledge that the nation has plentiful solar resources, it was logical not to put a limit on the technology. Published estimates of a solar potential of 27 MW [28] appear to be far too low, given that the NDC targets are set well above this potential and for physical land-use reasons described below. The modeling and results in this study are reflective of the NDC targets [2]. Government identified lands for renewable energy have been identified including land near the Parham Ridge Wind farm and the existing solar PV Bethesda array, which equate to around 0.8 km^2 of land [37]. Between approximately 90 km^2 of agricultural land on the island, parking areas, and commercial buildings, and more, land areas of up to 4 km^2 could be utilized for the remaining land needs for solar PV [49]. Storage limits were based on realistic limitations of the current technologies.

3.2.7 Land Use Description

Antigua's total area of 281 km^2 is also a limited resource to be considered, and consequently for each of the scenarios, the total land area requirement was estimated. In this analysis, only solar PV and CSP were taken into consideration. The direct land use of wind turbines is small, although the effective use of land and the visual footprint can be quite large. The land area used per MW was determined to be 17,000m^2/MW (1.7 hectares/MW) [50] for solar PV and 26,000m^2/MW (2.6 ha/MW) for CSP [41].

3.2.8 Job Creation and Destruction

Important to the energy system transition is the concept of a "just transition" from the current paradigm. Although the just transition involves many aspects, such as societal engagement and democratic processes, one key piece is that of changes in employment [51]. Employment impacts in the electricity sector in Antigua and Barbuda were calculated for each scenario using multipliers that were assigned to the different technologies based on construction and installation, operation and maintenance, and fuel supply. There is also a regional factor that considers the current workforce capabilities of the nation. As Antigua and Barbuda has minimal solar PV and no other renewable sources installed, there will be a lack of experience in the installation and maintenance within the workforce to begin this transition. Then, as time goes on and the workers gain experience, the number of people needed for the same amount of work will decrease. Appendix C details all the factors that contribute to each of these defined categories. These factors are defined in jobs/MW for operation and maintenance for the overall capacity of each technology or job-years/MW for construction and installation for the capacity added each year for each technology. For each scenario, a logistic growth to the final capacities as given in the optimization was used to estimate yearly job additions for each technology, as well as the jobs needed for operation and maintenance [52].

3.4 Results

3.4.1 Current Electricity System

Scenarios were developed with the assumption of finding electricity system configurations that are consistent with the NDC goals of 86% renewable energy generation of all electricity and 30,000 homes with solar systems [2]. To compare the different scenarios on an equivalent basis, a model of the current electricity system was created as a baseline. In all cases, a "green field" approach was used, with the assumption that no current system is in place. Therefore, the total cost and levelized costs shown in our results will be based on an annualized accounting with all capital and marginal costs accounted for. Thus, the model that is based on the real optimal system in Antigua including fuel oil generators is a likely counterfactual that would assume replacing current capacities a decade in the future; the assumption is that new generators would have to be bought by then even if the country were to continue down a business-as-usual pathway. In the case of fuel oil generators, the marginal cost is taken as US$0.17/kWh, and is a significant fraction of the total annualized cost.

Table 3: Current and 2035 Diesel Based Grids

Antigua Current and Future Business as Usual System		
Scenarios	**Current System**	**2035 System**
LCOE ($/MWh)	189	190

Diesel (MW)	53.5	66.8
Solar PV (MW)	9	9

Table 3 gives the LCOE found by the model when constrained to technologies currently in use, as well as the corresponding LCOE in the year 2035 with the assumed increase of demand by 20% and assuming that no more solar will be installed in that time. As would be expected, the LCOE will remain the same; these results are useful as a baseline to compare with other scenarios and tell us what the relative costs would be for maintaining or replacing the current system.

3.4.2 Wind, Solar PV, and Batteries Scenarios

In the first set of scenarios, only solar PV, wind and batteries are included. These technologies are the most common renewable energy sources that are widely used today and are explicitly included in Antigua and Barbuda's NDC goals. Thus, it was important to understand if these technologies alone would create a reliable and economical system. As described in the Methodology, it is important to consider that the costs of the systems are based on capital costs estimates for 2035. Table 4 shows the results of three scenarios with these technologies alone, differing in the maximum amount of wind capacity allowed as part of the solution space. It is important to note that these already represent 100% renewable energy, zero-carbon-emission scenarios, and that these scenarios demonstrate a slightly lower LCOE than the current and "business-as-usual" systems.

Table 4: Common Renewable Technologies Scenarios

	Solar PV, Wind, and Batteries Only		
Scenarios	**25 MW Wind Max**	**50 MW Wind Max**	**100 MW Wind Max**
LCOE ($/MWh)	169	155	154
Land Use (km^2)	10.3	7.6	7.1
Solar PV (MW)	608	448	420
Wind (MW)	25	50	73
Battery Storage (MWh)	1588	1796	1725
Hours of Storage (Hours)	26.5	29.9	28.75

These scenarios were arranged in a way that increased the wind capacity from 25 MW up to 100 MW. All these scenarios are at or below the LCOE of the baseline system by about 15%. However, the storage times were not limited in this scenario, which allows an estimate of the kinds of storage needed to bridge periods of low wind and solar resource that may occur at some hours of the year. As seen in Table 4, storage times of up to nearly 30 hours are required for each of the scenarios. An assumed 70 MW was given for the maximum output of the batteries, given the system peak load of 67.7 MW. These scenarios are not very reliable solutions for an energy system based on battery storage, which might be limited to 8-12 hours, even in the future and even with newer technologies such as Redox-Flow batteries [53]. It should also be noted that wind power plays an important role, and when limited to lower capacities as in the first two scenarios, the optimization wants to use as much wind capacity as possible.

3.4.3 Introduction of CSP with Wind, Solar PV, and Batteries

One of the main contributions of this present work was to examine the utility of CSP as an option in a (near-) 100% electricity system. Although levelized cost reductions were seen with the system of solar PV, wind, and long-term storage, it is important to find more realistic storage options.

CSP was included in three new scenarios with the other renewable technologies that were used in the previous models. Again, limits were set to wind capacity, however, for these models, there were also limits set on each of the energy storage systems. The CSP thermal storage was given a limit of 24 hours, with no limit on the battery storage again. The results with this technology included in the system with the stated limits are displayed in the following table.

Table 5: Renewables with CSP Scenarios

	Renewables with CSP		
Scenarios	**25 MW Wind Max**	**50 MW Wind Max**	**100 MW Wind Max**
LCOE ($/MWh)	136	128	127
Land Use (km^2)	7.5	6.6	6.5
Solar PV (MW)	380	370	367
Wind (MW)	25	50	53
CSP Solar Field (MW)	40	13	12
CSP Turbine (MW)	60	60	60
Battery Storage (MWh)/Hours of Storage	541/7.75hr	565/8hr	568/8hr
CSP Thermal Storage (MWh)/Hours of Storage	1440/24hr	1440/24hr	1440/24hr

The model results of these scenarios show significant cost reductions from the current system LCOE of 28%-33%. This decrease was due to the large energy storage provided by the CSP thermal tanks. Thus, the required utility-battery storage was only 8 hours, still not a storage time commonly available today, but projected for batteries in the near future. These results show a similar trend, that increasing the wind energy only somewhat affects the system LCOE. As in the first set of scenarios, limiting the wind capacity to 50 MW or less leads to a solution that drives toward the maximum of that constraint, but about 50 MW of wind capacity is the unconstrained optimum. Also, the land use for each of these scenarios was significantly less than those in the previous scenarios.

3.4.4 Addition of Hydrogen Storage

The final additional technology considered was that of electrolysis-generated hydrogen that could be stored for long periods of time if necessary, and then converted to electricity using fuel cells [54]. Several scenarios were run using hydrogen as one option. Table 6 shows results for a selection of system configurations.

Table 6: All Technologies Scenarios

Renewables with CSP & Hydrogen Storage			
Scenarios	**No Restrictions**	**Limited Wind (<25 MW); CSP Must be Included**	**Limited Wind (<25 MW); No CSP**
LCOE ($/MWh)	122	130	127
Land Use (km^2)	5.1	6.5	7.3
Solar PV (MW)	289	378	432
Wind (MW)	58	25	25
CSP Solar Field (MW)	8	4	N/A
CSP Turbine (MW)	53	60	N/A
Battery Storage (MWh)/Hours of Storage	420/6hr	420/6hr	420/6hr
CSP Thermal Storage (MWh)/Hours of Storage	1280/24.2hr	1440/24hr	N/A
Hydrogen Storage (MWh)	1721	885	2000
Hydrogen Electrolyser (MW)	23	41	67
Hydrogen Fuel Cell (MW)	15	17	45

These scenarios yield similar system LCOEs to those without hydrogen. However, it shows that the CSP could be replaced completely with hydrogen generation and storage to produce a slightly lower system LCOE. Limiting wind to 25 MW or less, the optimal system would exclude CSP. To test the sensitivity with respect to these two options, one scenario was run to identify the LCOE with a limited wind system that must include CSP to understand the cost of the system with both CSP and hydrogen storage. Although the scenario that requires CSP to be included has a higher LCOE than the scenario without, the uncertainty in technology costs in 2035 implies that these two cases are practically indistinguishable in cost. Including CSP decreases land use by nearly 1 square kilometer, a potential advantage. The combined systems with all technologies in use find that storage for utility batteries and CSP thermal storage are storage times that are in place today, although possibly slightly less common.

3.4.5 Small Diesel Systems Remaining

The scenarios presented thus far are considerably cheaper than the current system. In all cases, however, the inclusion of diesel has not been incorporated into these hypothetical electricity system models. Antigua is seeking to obtain 86% of energy production through renewable energy by 2030, so including some diesel generation in the system could be a very useful way to help meet this goal and to help in general with the transition to 100% renewable energy generation. Results from scenarios with all technologies included, including diesel generation, either unrestricted or limited to maximum capacities of 10 and 5 MW are shown in Table 7.

Table 7: Scenarios with Small Amounts of Diesel Generation

	Small Diesel Contribution		
Scenarios	**No Restrictions**	**10 MW Diesel**	**5 MW Diesel**
LCOE ($/MWh)	83	106	119
Land Use (km^2)	1.8	4.3	5.7
Solar PV (MW)	107	239	306
Wind (MW)	90	51	57
CSP Solar Field (MW)	0	10	19
CSP Turbine (MW)	0	60	60
Diesel (MW)	38.5	10	5
Battery Storage (MWh)/Hours of Storage	195/2.8hr	420/6hr	420/6hr
CSP Thermal Storage (MWh)/Hours of Storage	0	1433/23.9hr	1440/24hr
Renewable Energy Penetration (%)	88	97	99

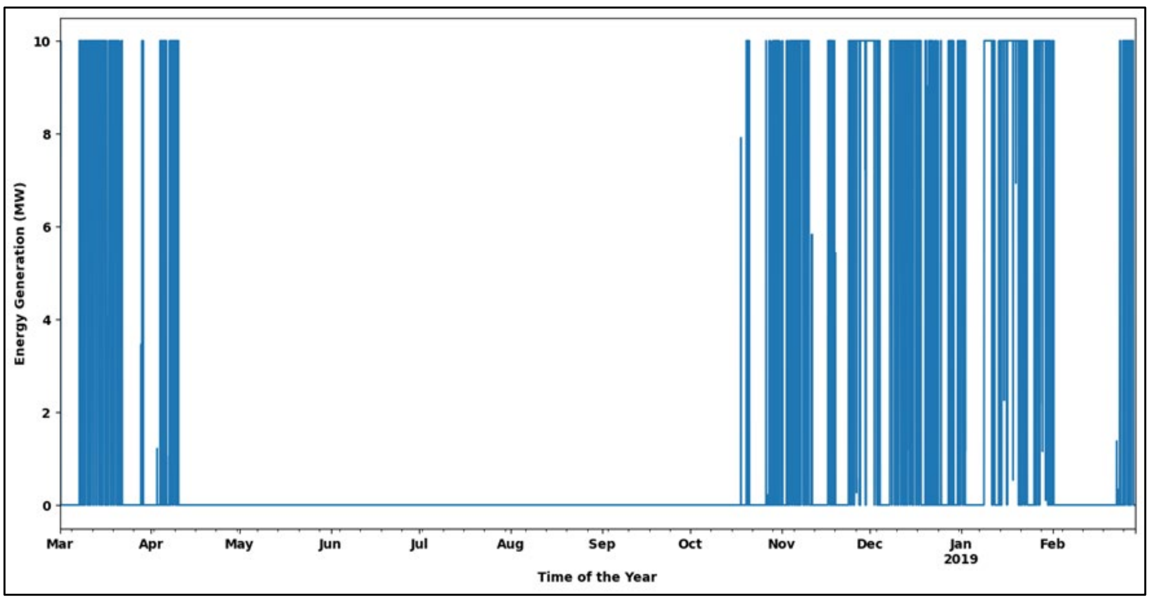

Figure 5: 10 MW Diesel Generation

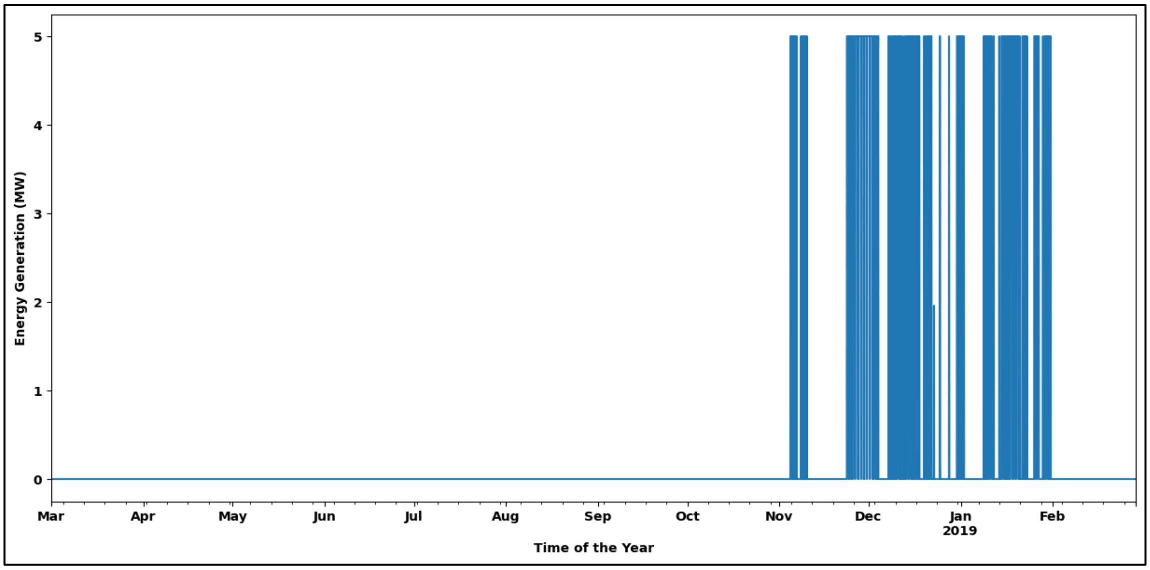

Figure 6: 5 MW Diesel Generation

The results shown in Table 7 have lower LCOEs than the previous sets of scenarios, although the 5 and 3 MW diesel systems are roughly the same as without any diesel capacity. These diesel systems do not actually generate much electricity, with capacity factors between 16% for the largest diesel system and only 7% for the 5 MW system. Thus, the diesel capacity acts as a flexible resource that runs only a few hundred hours each year, and it is implicitly assumed to be able to power on and off at will, a characteristic that may not reflect the reality of the larger diesel generators that are typical for Caribbean islands. However, there are technologies that allow for ramping to be done within a minute, thus allowing for these scenarios to be a reality with larger plants needed at low capacity factors [55]. It should be noted that the scenarios with larger amounts of diesel generation would require significantly less land than any of the other scenarios shown. In all these scenarios, the renewable energy generation is higher than the NDC target of 86% by 2030. Thus, any of these systems would allow Antigua to reach their goal. However, this could be accomplished with diesel generation that is constant, as their diesel plants would operate now, albeit at a low capacity factor.

Table 8: 7 MW Constant Diesel Generation

	Constant 7 MW Diesel Contribution		
Scenarios	**No Restrictions**	**No Hydrogen**	**No Hydrogen or CSP**
LCOE ($/MWh)	126	131	147
Land Use (km^2)	4.8	5.0	6.4
Solar PV (MW)	273	274	379
Wind (MW)	34	38	28
CSP Solar Field (MW)	7	14	N/A
CSP Turbine (MW)	35.5	60	N/A
Utility Storage (MWh)/Hours of Storage	473/6.8hr	476/6.8hr	1318/18.8hr
CSP Thermal Storage (MWh)/Hours of Storage	846/23.8hr	1413/23.55hr	N/A
Hydrogen Storage (MWh)	1123	N/A	N/A
Hydrogen Electrolyser (MW)	7	N/A	N/A
Hydrogen Fuel Cell (MW)	8	N/A	N/A

3.4.6 Summary of scenarios

Based on the assumed load for 2035, a constant 7 MW of diesel generation could be used to accomplish 86% of energy generated by renewable energy. The results in Table 8 show various scenarios that could be utilized in the transition to 100% renewable energy generation. These results show that the LCOE will be competitive to the other completely renewable and small-scale diesel generators that can be ramped on and off quickly and easily. However, this model shows again that having no CSP or hydrogen storage will drive up the LCOE quite significantly. Thus, at least one of these technologies could be extremely beneficial to the system to help decrease LCOE even if the technologies do not play the most important role in the system. It should be noted that results of numerous scenario variants (found on the Github repository) indicate that optimal solutions for nearly every scenario result in a CSP system with a 60 MW turbine with 24 hours of storage (1440 MWh).

3.4.7 Sensitivity Tests

A sensitivity analysis to the capital cost of solar PV and CSP and on the marginal cost of the diesel generation per MWh were done. Scenarios were run with assumed solar PV capital costs of $1200/kW and $550/kW rather than the baseline of $880/kW. CSP capital costs were increased by a factor of 1.2 ($3168/kW for solar field, $912/kW for turbine, and $60/kWh for storage) and decreased by a factor of 0.8 ($2,112/kW for solar field, $608/kW for turbine, and $40/kWh for storage) as sensitivity checks. Finally, the baseline marginal cost of diesel generation, $0.60/liter [56], was increased to $1/liter as the check for sensitivity of scenarios to higher fossil fuel costs.

For a system that had no restrictions with solar PV, wind, CSP, and utility storage and an increased cost of fuel oil, results in a system LCOE of $127/MWh but with no fossil fuel capacity, as shown in Table 9. That is, an increased fuel oil cost results in the system without fossil fuels being the lowest cost optimal solution.

For the sensitivity tests to capital costs for solar PV and CSP, constraints of 25 MW for wind energy, a maximum battery storage of 10 hours, and a maximum CSP storage time of 24 hours were implemented. Results are shown in Table 9 and Table 10.

Table 9: Diesel Fuel and Solar PV Sensitivity Tests

	Sensitivity Tests		
Scenarios	**Diesel Fuel Increased**	**Solar PV CAPEX Increased**	**Solar PV CAPEX Decreased**
LCOE ($/MWh)	127	153	108
Land Use (km^2)	6.6	7.3	8.2
Solar PV (MW)	367	341	461
Wind (MW)	52	25	25
CSP Solar Field (MW)	12	57	15
CSP Turbine (MW)	60	60	60
Diesel (MW)	0	N/A	N/A
Utility Storage (MWh)/Hours of Storage	568/8hr	519/7.4hr	577/8.25hr
CSP Thermal Storage (MWh)/Hours of Storage	1440/24hr	1440/24hr	1440/24hr

Table 10: CSP Sensitivity Tests

	Sensitivity Tests Continued		
Scenarios	**CSP CAPEX Increased**	**CSP CAPEX Decreased**	**CSP Extended Storage Time**
LCOE ($/MWh)	143	127	124
Land Use (km^2)	7.9	7.4	6.6
Solar PV (MW)	435	359	367
Wind (MW)	25	25	53
CSP Solar Field (MW)	19	49	12
CSP Turbine	60	60	40
Utility Storage (MWh)/Hours of Storage	606/8.7hr	529/7.75hr	568/8hr
CSP Thermal Storage (MWh)/Hours of Storage	1440/24hr	1440/24hr	1440/36hr

The cost for solar PV impacts the system LCOE most, with less sensitivity in resulting CSP storage time capacity and cost. Given the strong tendency in the past for solar PV costs to decrease and for the cost of oil on global markets to fluctuate, both the main results and the sensitivity tests indicate that a system based mainly on solar PV and with a gradual phase-out of fossil fuel generation will be economically advantageous.

3.4.8 Land Use Results

Land use is a key factor in these systems as renewable energy technologies take up considerably larger areas than fossil fuel plants do. Many of the scenarios required up to 8 km^2 of land for the solar PV and CSP plants. Based on the results from the scenarios, the land use of these technologies can be calculated. The land use for the solar PV and CSP are both relevant to available land in Antigua and the NDC targets that are set by the nation.

As indicators for land use, there are two large areas currently in use by the energy sector, the West Indies Oil Company facility and the site of the current generating capacity on Crabbs Peninsula, with a combined area of about 0.7 km^2 [57]. This is larger than the amount of space the CSP plants would occupy, at around 0.4 km^2, for a 15 MW plant, the average plant size for the scenarios allowing for CSP. This is also comparable to the space required for a 40 MW plant, needing around 1.1 km^2, being one of the largest plant sizes this study suggests.

The NDC target of installing solar panels on 30,000 houses [2], with an assumed 4 kW system each, requires around 2 km^2 of roofing space for a total of 120 MW of rooftop solar PV. Since a typical house in Antigua and Barbuda has 180 m^2 of area [57], the 30,000 homes represent approximately 5.5 km^2 of space, so more than half of all the roofing for these homes would be occupied with additional solar panels capable of being installed if loads rise beyond the needs a 4 kW solar system can provide. Although the entirety of most roofs in Antigua cannot be utilized for solar PV, as panels need to be flush to the roof, which requires more space, and need to be south facing to get optimal output. Regardless, there should be sufficient space with a margin of 3.5 km^2 of roofing compared to the 2 km^2 minimum calculated above. Parking areas and commercial, industrial and government buildings would also represent surfaces that could be used for solar PV without encroaching on new land. However, it does appear that on the order of 1.5-3.5 km^2 of additional land area (on an island of 281 km^2) may be required for installing enough capacity to meet the target of 100% renewable energy.

3.4.9 Job Creation/Destruction

Estimates for the proposed systems found significant job creation in all cases. Figure 7 and Figure 8 show the job creation from 2020 to 2040 for a scenario with CSP. The almost 90 MW of the currently installed electricity system accounts for around 60 jobs based on the assumptions made to calculate jobs required/created for this type of technology. The figures demonstrate there is not only a short-term increase in job creation (mainly due to construction), but a long-term increase as well for operation and maintenance. Although the optimizations were run for a “green-field” assumption for 2035, to estimate employment, an S-curve interpolation to that date was used as an approximation for the time dependance.

There are at least 500 jobs required for each of the scenarios that were analyzed. The technologies that create the most employment are solar and wind energy. Utility solar will especially require the greatest number of workers during construction because the size of the solar PV plants are substantially larger than any of the other technologies. As time goes on, it is clear that the number of jobs will continue to decrease after the peak in 2033, but it will still provide more jobs in Antigua and Barbuda than the current energy sector requires.

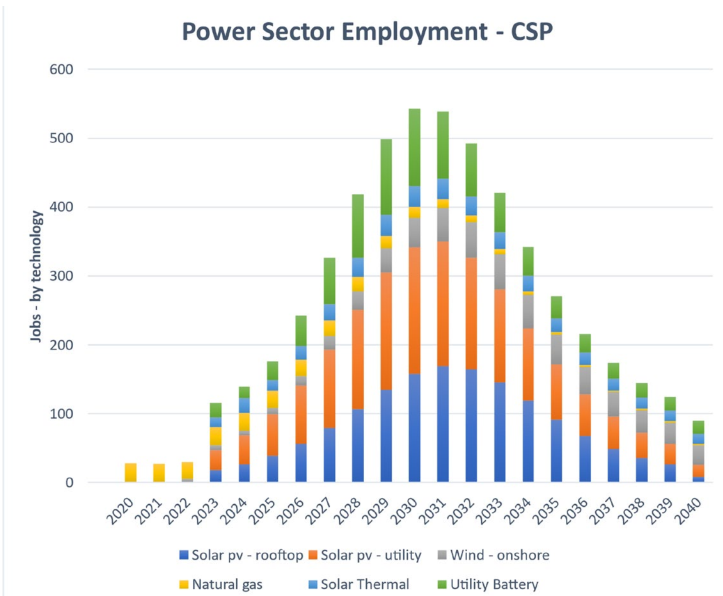

Figure 7: CSP Scenario by Technology

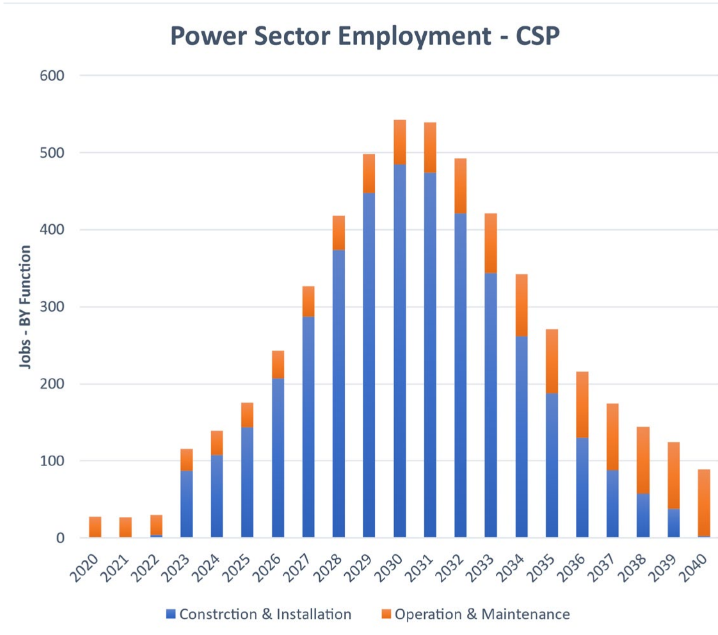

Figure 8: CSP Scenario Jobs by Function

3.5 Discussion

The results of this present study can be an important step toward understanding how more renewable energy can be implemented to meet Antigua and Barbuda's NDC target of 86% of energy produced by renewable energy for 2030 and in creating a strategy to meet that target [2]. All scenarios in our analysis achieve the target, and even in the scenario with remaining fossil-fuel technologies, diesel generation only accounts for 12% of total electricity generation. Thus, in an optimal system with the lowest LCOE at $83/MWh, the NDC target would already be met and seen as a large step toward achieving a system with 100% renewable electricity. However, as shown in the sensitivity tests, the optimum scenarios found with remaining fossil fuel generation are sensitive to the assumption that fuel oil will remain inexpensive; the overall long-term cost of the system with higher fuel costs is equivalent to that without any diesel generation. An advantage of the 100% renewable energy system is therefore an insensitivity to fluctuations in cost on global fossil-fuel markets.

The results in the present study are reflective of those found in IRENA's Renewable Energy Roadmap for Antigua & Barbuda [2]. This study analyzed the transition to a 100% Renewable Energy nation with the introduction of electric vehicles in the nation, too. Their results found LCOEs of around 0.10 USD/kWh (100 USD/MWh) with scenarios including small diesel plants and 100% renewable energy with hydrogen storage. The results found in this study are comparable to these results, with the addition of several more scenarios and a new technology, CSP.

The important goal of encouraging a "just transition," here represented though job impact considerations, can also be compared with a recent study. The results of the job impact assessment in this study can be compared to the results found from another recent study on Antigua & Barbuda's just transition [51]. The results found here show larger job needs for construction and implementation, but a smaller total of around 100 jobs compared to the 250 jobs found previously [51]. The energy system transformation clearly implies a transition in the nature of various economic sectors. To ensure a smooth and just transition to renewable energy, it is important to understand in greater detail the impact on jobs and livelihoods of those working in traditional fossil fuel-based industries. This study shows that each scenario will require at least as many jobs as the current electricity sector has now. Data gathering as more projects are implemented will be important to help policymakers develop effective strategies to support workers and mitigate any negative impacts of the transition to renewable energy.

One potential pathway forward from the current system would be to utilize small-scale diesel generation that many businesses and homes already have for emergency generation when the grid is unable to provide adequate energy across the island. These types of generators are able to power on and off easily and are more flexible than the large scale 10 MW generators. Thus, in scenarios where the diesel generators are limited to 10 and 5 MW where LCOE is lower than any other scenario, it may be feasible to rely on these small-scale generators for distributed backup generation for those times of the year that the renewables and storage cannot meet. Figure 5 and Figure 6 in the results section show how many of these hours are concentrated between the months of November to February.

Since many households and businesses already own diesel backup generators, a system solution could be feasible if coordination between distributed generation and the grid could be managed. Such a coordinated distributed system may also be a step towards 100% renewable energy generation, in which household solar generation, batteries and electric vehicles will provide the backbone for a combined smart grid. One important issue that will have to be considered is that of the distribution of the burden of costs for a transition; if, as suggested here, the renewable energy solution is the most cost-effective one, at least over the system lifetime, provisions will have to be made to ensure that those with lesser financial means can be part of that transition and not have to rely on the more expensive fossil-fuel options, such as personal backup generators.

In one of the main contributions of the present work, we find that the implementation of CSP helps to significantly drop the LCOE of the system and allow storage times that bridge the relatively rare longer periods of low solar PV and wind energy, compared to those scenarios with only variable renewables and utility-scale batteries. For most scenarios and under most constraints, the optimization model chose to include CSP as part of the system, showing that the technology is well suited for the island context. These results can be extrapolated to model energy systems for other nations in the Caribbean or island states in other regions around the world. The capability to expand this study to other nations and regions would be valuable considering Antigua has a bare repertoire of renewable energy resources with no dispatchable renewable energy sources.

Another key outcome of the scenario selection is that increasing wind power from 25 to 50 MW decreases the LCOE of the system noticeably for every combination of technologies, but the LCOE will only decrease very slightly with systems larger than 50 MW. Finally, the implementation of hydrogen generation and storage will create a similar reduction in LCOE as CSP. Our results provide a range of possibilities, thus allowing policymakers to gain a better understanding of how different technologies might perform in different contexts, which can inform decisions about where to invest resources and which technologies to prioritize.

Another important consideration is public and governmental trust in different technologies. In some scenarios, certain technologies may be more widely accepted and trusted, while others may face more resistance or skepticism.

By considering scenarios that reflect varying levels of public trust, policymakers can identify potential barriers to the adoption of certain technologies and develop strategies to address them. This could involve investing in public education campaigns or conducting outreach to build trust and understanding around specific technologies.

In conclusion, these results show that there is no single defined pathway towards a 100% renewable energy system. These results are likely reflected in other nations in the Caribbean who share similar resources and current energy sectors. However, in most other Eastern Caribbean countries there are geothermal or hydropower resources that can be effectively used as dispatchable resources to enable greater penetration of the cheapest renewable energy sources, wind and solar PV. The present work shows that even in the more challenging case of Antigua and Barbuda, 100% renewable electricity systems are viable and significantly less costly than current power systems.

Data Availability Statement: Data files, CSP and PV model spreadsheets, PyPSA code and Jupyter notebooks available on Github at https://github.com/RJBrecha/Hoody_Antigua .

Appendix A – Levelized Cost of Electricity

The levelized cost of electricity (LCOE) is an important characteristic of an energy system to determine if it will be an economically viable system for a given load. The LCOE is a value found by adding up the lifetime discounted cost of an electricity plant including capital and marginal costs, divided by the total units of electricity the plant will generate in its lifetime. In the models used in this paper the LCOE for the system is given in terms of $/MWh of electricity generated by system as a whole, not for individual technologies. All of the capital and marginal costs associated with a given system in this analysis can be added together and then divided by the total yearly load to find a LCOE for the given system. Thus, the lower the LCOE that is calculated, the more economically viable the system will be.

Appendix B – Capital Recovery Factor Scaling

A capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time [58]. This capital recovery factor can be defined with the following equation:

$$CRF = \frac{(i*(i+1)^n}{(i+1)^{n-1}} \quad (1)$$

The variable i is the discount rate and the variable n is the lifetime of the plant in years. In this scenario, i was assumed at a value of 7%, or 0.07, and n was assumed at a conservative value of 25 years (15 years was used for utility batteries). Using Equation 1 and multiplying the values in Table 1 and Table 2 in the methodology section results in the values shown in Table B- 1 and Table B- 2 below.

Table B- 1: CRF Multiplied by Generator and Link Capital Costs Together with Marginal Costs

Generator	Capital Cost ($/kW)	Marginal Cost ($/MWh)
Diesel	154.46	170
Wind	115.84	N/A
Solar PV	75.51	N/A
Concentrating Solar Power Solar Field	226.54	N/A

Concentrated Solar Power Turbine	65.22	N/A
Hydrogen Electrolyser	85.81	N/A
Hydrogen Fuel Cell	42.91	N/A

Table B- 2: CRF Multiplied Store Capital Costs

Stores	Capital Cost ($/kWh)
Utility Battery	143
CSP Thermal Storage	50
Hydrogen Storage	33.33

Appendix C – Employment Factors and Job Creation

Values for total capacity of each technology and capacity added each year are used in conjunction with employment factors to find jobs/MW and job years/MW for each technology in terms of construction and installation (C&I) and operation and maintenance (O&M), as well as the total job impact of the jobs in the electricity sector [59]. This was done on a yearly basis using a logistic curve to implement the system over a given period of time as would be more realistic than implementation all at once. Then, to find the required diesel system, an approach that found the kWh/kW_{power} for renewable energy generator technology then multiplying the found MW capacity calculated from the logistic curve of these technologies was required. These total generation values were summed together and subtracted from the yearly load and then divided by the number of hours in a year, 8,760 hours. Finally, this was adjusted by multiplying the value by 1.9 because the current system is much larger than just the load divided by the number of hours due to maintenance, large peak loads, etc.

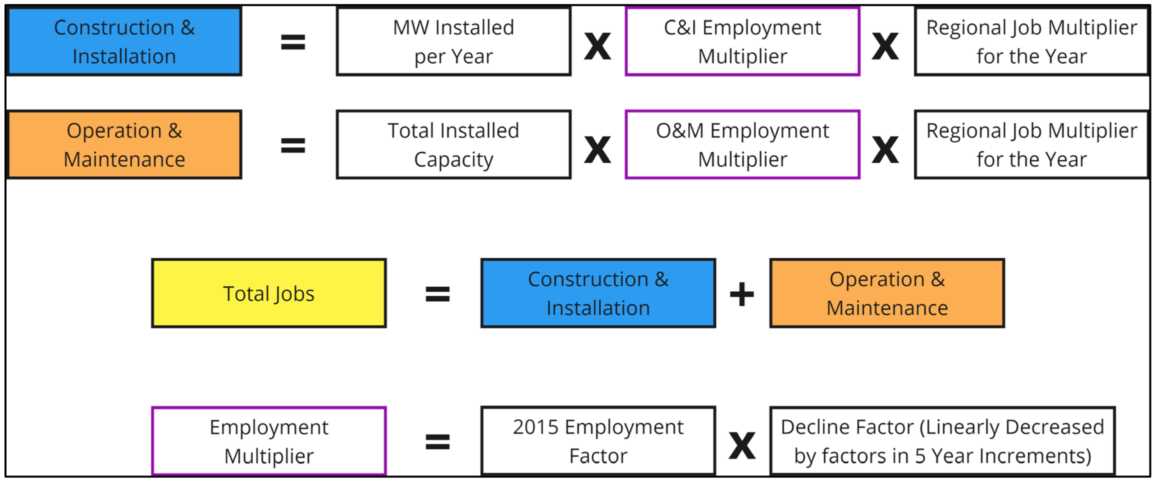

Figure C- 1: Job Impact Considerations

Job creation analyses were conducted for several scenarios including those without CSP and with hydrogen storage and without hydrogen or CSP. All those scenarios show that solar PV will dominate job creation but necessarily job sustenance. The utility battery storage appears to have a significant portion of job sustenance, but overall, the technologies share similar portions of job needs of the entire electricity sector. Wind energy will be another large contributor to job creation for those scenarios. Also, all the scenarios follow a similar trend in showing a large increase in jobs until 2033, where it will peak and then slowly but slightly decrease and plateau.

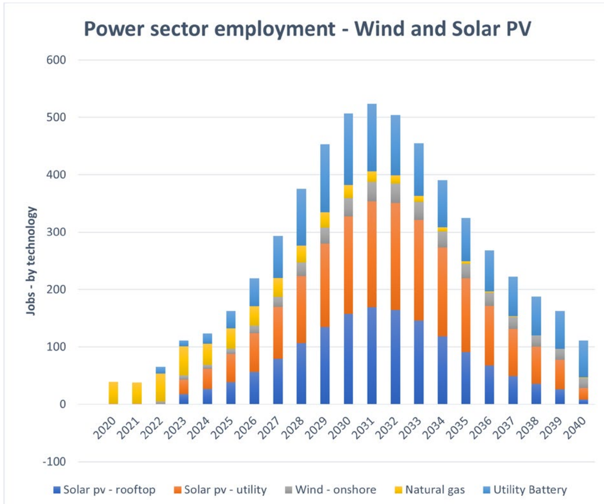

Figure C- 2: Wind and Solar PV Scenario Jobs by Technology

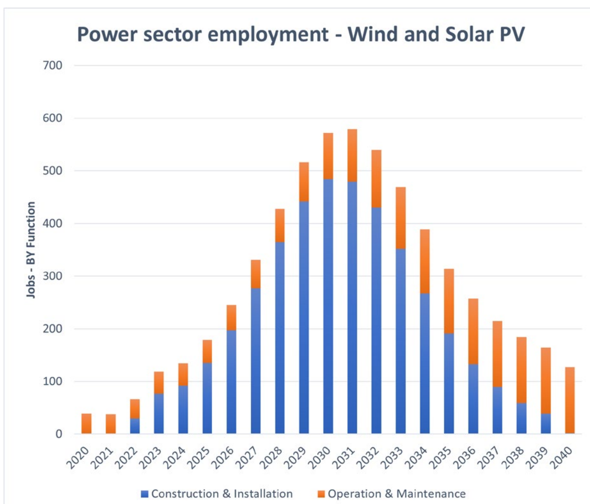

Figure C- 3: Wind and Solar PV Scenario Jobs by Function

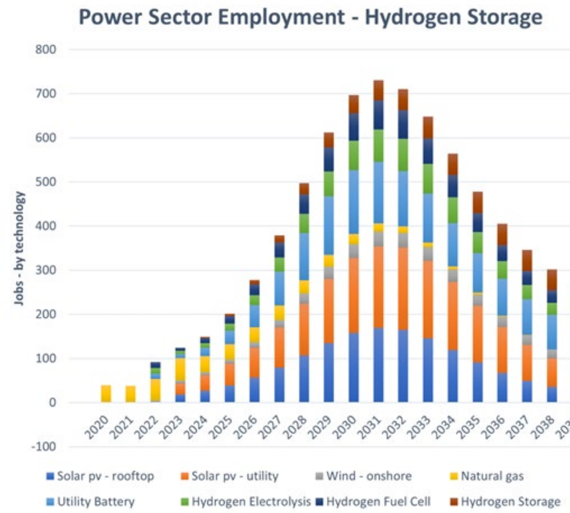

Figure C- 4: Hydrogen Scenario Jobs by Technology

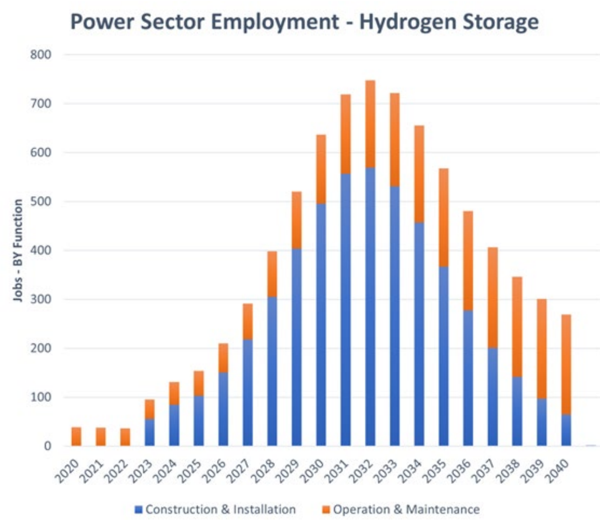

Figure C- 5: Hydrogen Scenario Jobs by Function

Appendix D – Details of CSP Calculations

The PyPSA model requires hourly input data, but since typical, representative hourly solar radiation data are not readily available for the project site, we used satellitite-derived data for the year 2021 from NASA POWER [22] The hourly data included the clearness index, air temperature, latitude, longitude, and solar radiation on horizontal. Monthly average daily solar radiation for the year 2021 from NASA POWER [22] are compared to typical values from NASA POWER [22] in Figure D- 1. An inspection of Figure D-1 reveals that average daily solar radiation for 2021 varies little from typical, ranging from differences of 0.4% in January to about 10% in November. On an annual basis, average daily solar radiation in 2021 was 2.75% greater than typical.

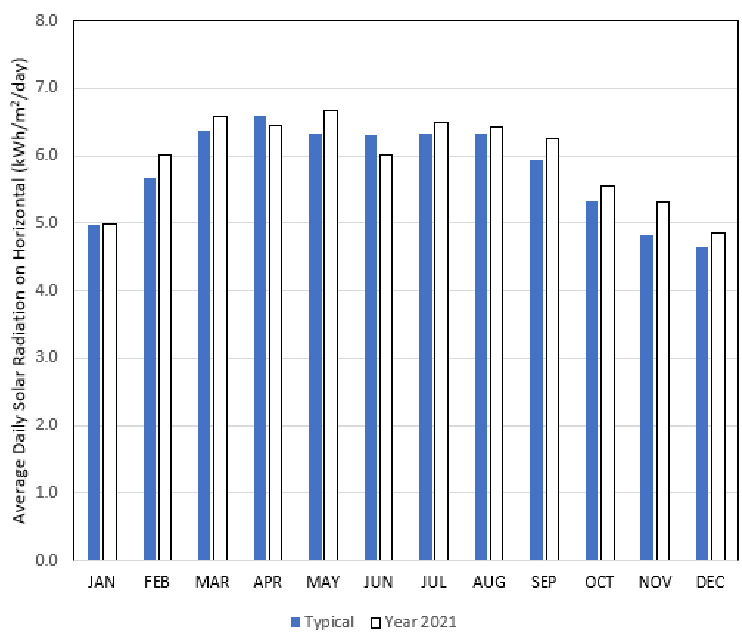

Figure D- 1: Comparison of typical monthly average daily solar radiation on horizontal to actual values from 2021

The projected hourly output of electricity of the PV arrays and CSP plant were used as input to the PyPSA model. To utilize total horizontal solar irradiation data from NASA, a methodology is needed to estimate beam and diffuse fractions, and thus algorithms described by [60] were used in this study. To summarize, Equations 2 and 3 are first used to find the diffuse radiation on the tilted surface. Equation 4 is used to find the solar radiation on the tilted surface Equation 5 calculates the ground diffuse radiation that is combined with the sky diffuse radiation for solar PV. The process is shown in Figure D- 2.

$$I_d = I_{dH} \quad (2)$$

$$I_{d\theta} = I_d \times F_{SS} \quad (3)$$

$$I_{D\theta} = \left(\frac{I_{DH}}{\cos\theta_H}\right) \times \cos\theta \quad (4)$$

$$I_{R\theta} = I_{TH} \times \rho \times F_{SG} \quad (5)$$

where I is hourly solar radiation, FSS is the surface-sky view factor, θ is the solar incidence angle, subscript d is diffuse, subscript D is beam.

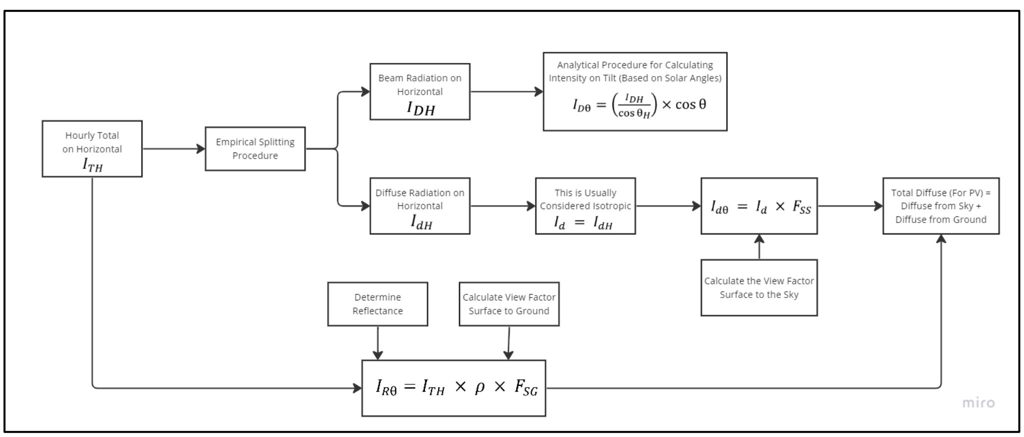

Figure D- 2: Calculating beam radiation from total horizontal

The useful heat output from the concentrating parabolic array was calculated from the beam radiation, ambient temperature, fluid temperature entering the collectors, array size, and the solar incidence angle using algorithms from Duffie and Beckman [60]. The useful thermal energy from the solar array was then used to calculate the amount of energy converted to electrical energy by calculating the actual Rankine power cycle efficiency as a function of the Carnot efficiency. The total solar radiation on the tilted PV surface, in conjunction with rated efficiency corrected for the current hourly PV cell temperature, was used to determine the PV electrical energy output. The key differences between the solar PV and CSP calculations are that the solar PV uses total diffuse (ground and direct) whereas the CSP uses on direct radiation and the CSP model has the capability to generate up to its nameplate capacity where PV only reaches about 75% of its nameplate capacity due to inherent losses in conversion from DC to AC power.

Data files and the CSP model spreadsheets are available on Github at https://github.com/RJBrecha/Hoody_Antigua. PyPSA only needs a scaled output for relative capacity, with the optimization "finding" the optimal capacity and the time-dependent output. The storage time, or more precisely, the ratio of energy storage capacity (MWh) to power output (MW) is maximized at 24 hours, which the modelling determined to result in the lowest LCOE.

As mentioned in the Methodology, the capital costs of the CSP generation and storage are described based on the electrical output and storage size. The storage capital costs were found using proportions of real CSP plant cost breakdowns. Based on studies such as two of IRENA's studies, a breakdown from the total capital cost of 85% for generation and 15% for storage were used to find the cost per MWh [48], [61]. This is reflected in the Github material.

4 Internship at the Department of Environment in Antigua and Barbuda

4.1 Introduction

This section outlines the projects worked on, deliverables achieved, reflections, and other experiences gained during my ETHOS experience with the Department of Environment in June and July of 2023. These experiences reflect the discrepancies that occur between the optimal systems described above and the work, barriers, assets, and other considerations that cannot be ignored in the transition. These are based on the personal experiences and relationships I had the privilege of obtaining during my ETHOS experience and internship.

4.2 Overview of the Department of the Environment (DOE)

The Department of Environment is a governmental department under the Ministry of Health, Wellness, and the Environment. The mission of the DOE is stated as "The overall mission of the DOE is to provide technical advice and implement projects and programs on behalf of the Government and the people of Antigua and Barbuda. These projects are designed to protect and enhance the country's environment, as well as seek common solutions to national, regional, and global environmental problems" [62].

The DOE in Antigua and Barbuda plays a pivotal role in achieving its mission through a multifaceted approach. Their primary objective is to preserve and enhance the nation's environment. This mission is accomplished through environmental planning and management systems, supported by active public participation and collaboration with international agencies. Furthermore, they emphasize the efficient implementation of appropriate programs and technical services to address environmental concerns.

The department guides environmental management while ensuring effective and consistent enforcement of environmental laws and regulations. They prioritize making environmental information easily accessible to the public and offer technical assistance on various environmental issues. This aims to raise awareness and promote responsible environmental practices among the citizens of Antigua and Barbuda.

Collaboration is essential in the Department of Environment. They work closely with consultants, international agencies, stakeholders, and contractors to identify and implement best practices in various projects. This collaborative effort spans many sectors and aspects of life in the nation, reflecting the department's commitment to environmental preservation in Antigua and Barbuda.

4.3 Overview of Projects

In my work, one of the projects that took most of my time was work with the Sustainable Pathways for Protected Areas and Renewable Energy (SPPARE) Project, in particular, the Abu Dhabi Fund for Development (ADFD) Wind Turbine installations. One of the tasks I had was to create a manual for the foundation creation of the Vergnet hurricane-resistant wind turbines to allow future contractors to produce

Figure 9: Construction Site of Hurricane-Resistant Wind Turbines. Source: [63]

these foundations easily and efficiently for any additional turbines. A second task I had was to create media on the process of the installation. To do this, I took 2-minute videos of the installation at different points in the process, seen in Figure 9 [63]. I needed to mark a spot for the tripod and align it well for the videos to flow well. Then, I used a video editor to make the final presentation of the installation. This could be utilized to help future installations or be used for social media, advocacy, etc. Finally, I worked with the drill rig operator and a supervisor of mine at the DOE to get the required holes drilled for foundations, keep updated on the surveying status, and work with another coworker to get equipment ready for land clearing.

The drilling was needed for large holes in the ground that were utilized for the foundations of the hurricane-resistant wind turbines. On a basic level, I needed to help align the drill rig by ensuring it would pass through a designated point by land surveyors and that it is parallel or perpendicular to a line, also designated by the surveyors, the holes need to be aligned with to properly support the weight of the turbines. This process was documented in detail in the manual created for the foundation creation. This was one of the two main projects I worked on.

The other project that took the most of my effort and time during my experience at the DOE was the SLIM (Sustainable Low-Emission Island Mobility) E-mobility project. The focus of this project during my time there was to identify potential sites to send expression of interest forms for charging stations that can then be further assessed by technical consultants. To accomplish this, we visited many parking lots and general parking areas across the island for public buildings to quantitatively evaluate them. They were scored on many factors including parking lot size, security presence, proximity to the main road, typical duration of stay, presence of businesses nearby, and much more. Once all sites were assessed, we mapped the locations that scored above a certain threshold to identify if there would be locations spread across the island to help with the EV transition. We were pleased to see that there were locations all across the island that scored well. Based on these results, they are currently working to evaluate the feasibility of installations at each site with a technical consultant. The SLIM E-Mobility work that I was able to work on finished with several deliverables.

The most prominent deliverable was the creation of a map of the potential sites that scored above the low limit that the team set. The map shown in Figure 10 displays that there are suitable parking lots of public sector buildings all over the island. However, there is a large concentration of suitable parking lots in St. John's. Another deliverable that came from this project while I was able to work on it was a methodology of the site assessments. It has not yet been completed, but it is in its final stage of development. Several other projects took up less of my time, which I was also able to produce deliverables for.

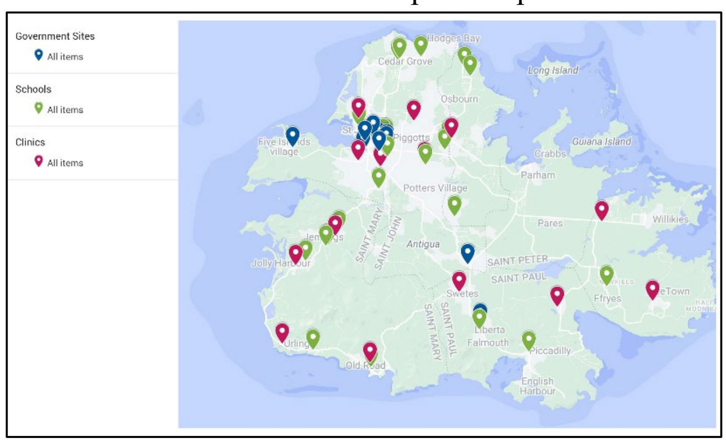

Figure 10: Map of Potential Charging Station Sites

First, I helped with the National Adaptation Plan (NAP). I worked on the implementation and youth sections. I only created drafts as they will be further developed and perfected for the final NAP to be finished next year. Another project I contributed to was data gathering for the eighth replenishment of resources of the Global Environment Facility trust fund (GEF-8). We were able to gather much data and documents about various projects and documents around the DOE that were needed for this funding. A final deliverable was working on the DOE’s Data Management System (DMS). I wrote a code that would process data from a specific typical inverter for solar systems on the island. This work aims to be able to analyze if the solar systems are operating as intended.

4.4 Overview of the University of Dayton Internship Program

The University of Dayton's ETHOS Center, in the School of Engineering, has developed partnerships around the world, including regions such as South America, India, Africa, and notably, Antigua & Barbuda. They offer several international immersions including a 10-week program, aiming to develop both technical expertise and personal growth through work and cultural immersion for students. The ETHOS Center is dedicated to encouraging critically reflective global citizens who consider the sociocultural dimension of engineering that will continue into the students’ careers.

This program challenges students to take on inclusive and holistic approaches as they learn new ways that people of different cultures and backgrounds approach engineering problems. Students cultivate cultural humility, vocational discernment, practical wisdom, and a commitment to social responsibility. As a result, they emerge with a passion for the common good, a dedication to justice, and various global competence skills. Technical capabilities are developed in an interdisciplinary and creative manner. Finally, students can apply their knowledge and skills to support human rights, social justice, and environmental well-being.

4.5 Challenges Faced

During my internship at the DOE, I encountered several challenges that tested my knowledge and adaptability. One notable challenge revolved around effective communication. On numerous occasions, I encountered difficulties in fully comprehending the requests and instructions presented to me. To overcome this obstacle, I needed to find clarification, often requiring asking clarifying questions or asking other coworkers to ensure I understood the details of my assigned tasks. It was essential for me to understand the goal of the projects, particularly when the instructions or information were not fully defined.

Another challenge arose in the context of engaging with stakeholders through phone calls. Not fully understanding certain aspects of the local dialect made some communication difficult. It was not uncommon to be slightly frustrated when calls went unanswered, or the quality of communication was poor. Some stakeholders expressed limited interest in our inquiries or updates, further adding to the challenge.

Finally, I encountered many interruptions and stoppages in the projects I worked on. There were instances where projects I was involved in were halted due to various factors. These delays could be attributed to the need for essential input from the DOE or stakeholders, or they could result from coordination challenges with contractors. All sorts of tasks, such as organizing site visits, could be very difficult, contributing to unforeseen challenges and consequent time inefficiencies. A challenge that pushed back a project's timeline substantially was an issue with equipment for the wind turbine installations. There was a specific machine essential for the progression of the project, but there was only one on the island. Due to an unexpected break in the utilization of the machine, it was used for other governmental work. Consequently, the machine was used for this work and delayed the work on the wind turbines by weeks which created complications for various other portions of the project.

4.6 Experiences in Antigua & Barbuda

During my time in Antigua & Barbuda, I was able to participate in many cultural and work experiences that enabled me to learn about the culture and how the environment is incorporated into it. There was one specific cultural experience that the Department of Environment (DOE) allowed us to participate in. This was a memorable experience presented to us at the nation's Carnival launch parade, where we got to help showcase an EV for a raffle the DOE was hosting. Observing people's interest as they took photos of the EV filled me with hope that sustainable transportation was sparking curiosity and appeal by those present at the launch. Through the DOE, I was also allowed to attend a UNICEF workshop. Witnessing the work of an international organization that brings people together to address the nation's needs was unique. Also, being part of meetings with international agencies like NREL and IRENA, as well as collaborating with consultants on diverse projects, was a very valuable experience I am grateful for. Meeting and learning from people all over the world who were trying to help the nation move towards a sustainable future allowed me to learn how experts can contribute to the nation's efforts while considering the nation's context.

During the experience, my coworkers recommended exploring the island's beaches. We visited beaches all over the island. Despite sargassum seaweed affecting some East Coast beaches, I was able to partake in much snorkeling where I was able to see vibrant marine life, including fish, starfish, turtles, jellyfish, crabs, and even a stingray. I was also able to learn about the local music culture, immersing myself in Soca music, which I have truly come to appreciate. I was able to attend a concert with the other ETHOS students featuring a popular Soca artist. I'm grateful for not only learning about the music but also receiving guidance on where to experience it fully.

My coworkers spent much time with us as they introduced the island's highlights. This time was spent on the beaches, on hikes, and sharing many meals. They extended invitations to spend time with their friends, allowing us to connect with numerous people. We took advantage of the opportunities to explore the island's scenic landscapes on several hikes with colleagues, as can be viewed in Figure 11 [64].

Figure 11: View from a hike with a coworker and another ETHOS student. Source: [64]

While not all hikes went as planned, they were some of my favorite experiences outside of work.

4.7 Barriers toward the Transition to a Renewable Energy Electric Grid

My time spent in Antigua and Barbuda has allowed me to understand the intricate relationships, dynamics, and departments that play pivotal roles in the nation's transition to renewable energy. This experience has revealed several significant barriers that hinder this transition. These relationships were proven to be complicated, arising from various motivations, and hidden underneath the surface. These barriers have been significant in the transition thus far and will likely continue to have a significant impact on the transition.

One obstacle is the influence of the people and companies that play a significant role in power generation and distribution. There is an economic benefit for various parties to support these companies which shape policies that promote the use of fossil fuels in energy generation. This impedes the integration of new renewable energy projects into the grid. The economic interests tied to the existing energy infrastructure create a challenging environment for transition efforts.

Another barrier is the high costs associated with renewable energy projects in comparison to the nation's income levels. As described earlier in the thesis, Antigua and Barbuda is classified as a high-income state, but the average income remains low when compared with the cost of living. Renewable energy projects in the region often mirror or exceed the expenses incurred in wealthier nations. Moreover, the lack of standardization and the need to import most components present substantial challenges for small-scale installations, particularly without substantial international funding.

Timelines and project delays constitute yet another barrier in the transition to renewable energy. A significant portion of funding for these projects is provided by international agencies, which frequently require strict deadlines and reporting. However, the availability of a workforce, expertise, and equipment on the island may not always align with these timelines. This misalignment can lead to delays, hindering the progression of renewable energy initiatives. These barriers, arising from complex relationships between stakeholders, economic factors, and resource limitations, represent critical challenges that Antigua and Barbuda must address to achieve a successful transition to renewable energy. This barrier especially reflects the importance of healthy relationships as an asset in the transition to renewable energy in the nation. Considering the small population on the island, it is essential that relationships are prioritized between all those working towards this goal. As I was able to experience, there were several relationships that presented dramatic challenges that caused delays in projects, diminished the impact of the projects, or may completely end the progress of some projects.

Finally, with all of these barriers in mind, funding is a final barrier that the nation faces as it looks to transition to renewable energy and mitigate and adapt to climate change. The Department of Environment has had the privilege to find funding through several international agencies and funds including the Abu Dhabi Fund for Development and the Green Climate Fund. However, as delays and barriers present themselves, the funding can be paused, pulled, or more may be required with unexpected delays and challenges that must be overcome. There must be effective communication between these funds and the work done on the ground. As the agencies work with nations, they must have some perspective for the real relationships and barriers that are faced with the project implementation that should be considered and understood when working towards the nation's goals.

4.5 Conclusions

I am very grateful for the opportunity to partake in the summer 2023 internship at the DOE, funded through the honors program and facilitated by the ETHOS Center. My gratitude extends to the warm and welcoming people who made our experience so engaging and educational. Virtually everyone we had the privilege to interact with went out of their way to offer recommendations for beaches, hikes, and other activities, enhancing our personal experiences beyond the realm of work.

Moreover, I am thankful for the trust and opportunities extended by our coworkers. This internship allowed me to contribute to a wind turbine project, an experience that I am extremely grateful to contribute to. It broadened my understanding of the details involved in planning for the transition to electric vehicles, knowledge that I had experience with before this opportunity.

This experience was very fulfilling, and I hope that my contributions have left a positive mark on the ongoing and all-important work at the DOE. While I wish some of the projects I was involved in could have progressed further during my time here, I know I invested my best efforts in advancing them. Meeting and collaborating with both colleagues and individuals outside of work was a privilege that I will take the learnings from into the rest of my life and career. The opportunity to connect with people from diverse backgrounds is something I cherish, and I look forward to maintaining these connections with those I've had the pleasure of getting to know here.

5 Conclusion

In the pursuit of renewable energy implementation in Antigua and Barbuda, this research sought to identify the balance between theoretical ideals and the realities that shape the nation's energy landscape. The overarching goal was to identify the theoretical optimal energy system. Then, during the ETHOS experience, the intricate challenges posed by implementation were acknowledged and identified. This endeavor echoes the principles of a "just transition," a concept increasingly vital in the global effort to transform energy systems while safeguarding economic and social equity.

The idealized energy system that integrates renewable energy technologies like Concentrated Solar Power (CSP) is an important assessment done in this work. The details of CSP systems were discovered to be a valuable addition to the project of achieving all of the goals outlined in the nation’s Nationally Determined Contribution. Long-term storage provides a valuable asset as the nation is restricted to renewable energy technologies of only variable technologies.

Within the realm of sustainable energy development, the concept of a "just transition" serves as a moral compass. It underscores the need to ensure that the journey towards cleaner, more resilient energy systems does not leave vulnerable communities or workers behind. It underscores the importance of social equity, job creation, and community engagement in the pursuit of sustainability. In Antigua and Barbuda, as in many regions, this concept takes on added significance. As we consider the transformation of the energy sector, it is imperative to prioritize the well-being of the nation's people, acknowledging that the real-world application of optimal theoretical systems must align with this commitment to justice.

This research has culminated in a publication that encapsulates the theoretical insights, modeling efforts, and analyses undertaken. Implementation of CSP can help reduce electricity costs from a solar, wind, and battery storage system by up to $30/MWh. Also, a renewable energy-based grid system could increase long-term job opportunities and requirements by around threefold with the current energy generation workforce of around 30 people. However, it is vital to acknowledge that the real work that will occur in Antigua and Barbuda's energy sector will differ from the idealized scenarios presented here. Thus, it was important to provide several combinations of technologies that can achieve its goals based on public trust and the dynamics of policymaking, the intricacies of market forces, and the evolving needs of the nation's communities that play a pivotal role in shaping the path forward. While this publication provides a solid foundation, it is merely a starting point for the substantial efforts that lie ahead.

The pursuit of sustainable energy in Antigua and Barbuda is a very complicated and long-term endeavor. The journey from theory to reality is both a challenging and an inspiring one. As we embark on this path, it is essential to remain agile, adaptable, and attentive to the unique needs of the nation and its people. The publication serves as a roadmap, but the journey will be marked by its distinct challenges and victories, as the nation strives to build a more sustainable and just energy future for Antigua and Barbuda.

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