UNIVERSITY OF FLENSBURG

DOCTORAL THESIS

A 100% renewable energy system for Small Island Developing States using open-source energy system modelling tools to examine Barbadian energy system as an example.

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A thesis submitted in fulfilment of the requirements for a degree of Dr. rer. pol

In the

Interdisciplinary Institute for Environmental Social and Human Sciences
Department of Energy and Environmental Management

May, 2024

Abstract

Despite being a minuscule contributor to global greenhouse gas emissions, the Small Island Developing (SID) State of Barbados is highly vulnerable to hurricanes, rising temperatures, and other potential impacts of climate change. Also, the island can be characterized by a high dependence on fossil fuel, resulting in high-cost of living and debt accumulation, which drains foreign reserves and national resources. Consequently, a 100% renewable energy system (RES) target is necessary for climate change mitigation and socio-economic survival. However, most energy system modelling and scenario analysis were conducted with closed black box energy system models; thus, more transparent open-source energy system modelling tools were proposed to examine the transition to higher shares of renewable energy. Using the greenfield approach and the Oemof modelling framework to investigate the cost-optimal and 100% renewable energy system configurations, cost-optimal energy mixes over 90% renewable energy possible with levelized costs ranging from 0.17 to 0.36 BBD/kWh with a marginal increase for the 100% renewable energy systems. Despite seasonal variations in wind resources, wind is a critical renewable energy resource matching the seasonal shore-to-ship power of the cruise industry and covering the uncontrolled transportation charging. Including cheaper solar PV resources at the utility scale reduces the annualized investment costs albeit with a slight reduction in levelized energy costs. Dispatchable generation is a significant driver of energy system costs; any dispatchable options for Barbados must be highly flexible to support the final 100% renewable energy system. Pump hydro storage was the cheapest option for Barbados, provided favorable geological studies support the suitability of the location identified in the study. The QGIS open-source platform was used to successfully map the power grid in PyPSA, which supports the current grid and will require significant expansion, especially in the north, centre, and east, to accommodate the utility scale wind resources, flexible generation and pump hydro storage.

Acknowledgments

I would like to express my deepest gratitude to the Ministry of Education, Technological and Vocational Training, as well as the National Development Scholarship Programme and Committee, for selecting and enabling me to pursue this study. Their support has been instrumental in making this journey possible. I also extend my sincere thanks to the Barbados Defence Force for the invaluable accommodations that allowed me to undertake these studies. A special note of appreciation goes to the Ministry of Energy and Business and its dedicated officers, whose collaboration and insights proved invaluable throughout this entire process. A special thanks to the Barbados Port and all other energy sector shareholder involved with sharing of information and insight.

I am profoundly grateful to my supervisors at the University of Flensburg for their invaluable guidance throughout the course of this research. To my fellow researchers, that aided in my publication and modelling, I thank you. To my dear friends and mentors around the world—you know who you are—I am eternally thankful for your steadfast support, encouragement, and belief in me. Your carried me through the challenges of this journey, and I could not have done it without you. Above all, I thank God for the grace and strength to complete this journey.

List of Abbreviations
Atlantic; Indian Ocean, Mediterranean and South China Sea (AIMS)
Barbados Light and Power (BL&P)
Barbados National Oil Company Limited (BNOCL)
Barbados Terminal Corporation (BTC)
Battery electric vehicle (BEV)
Coronavirus disease 2019 (COVID-19)
Critical excess electricity production (CEEP)
Demand-side management (DSM)
Division of Energy and Telecommunications (DET)
Electric Light and Power Act (ELPA)
Energy System Model (ESM)
Energy System Models (ESMS)
Fixed Operation and Maintenance (FOM)
Fuel Clause Adjustment (FCA)
Geographic Information System (GIS)
Global Financial Crisis (GFC)
Government of Barbados (GoB)
Greenhouse Gas Emissions (GHG)
Gross domestic product (GDP)
Independent Power Producer (IPP)
Inter-American Development (IADB)
International Renewable Energy Agency (IRENA)
Levelized Cost of Energy (LCOE)
Levelized Cost-Optimal System (LCOS)
Linear Programming (LP)
Low Emissions Analysis Platform (LEAP)
National Petroleum Corporation (NPC)
National Renewable Energy Laboratory (NREL)

List of Abbreviations
OEMoF/oemof (Open Energy Modelling Framework)
OSeEM-Barbados (OSeEM-Barbados)
Photovoltaics (PV)
Python for Power System Analysis (PyPSA)
Renewable energy (RE)
Renewable Energy Pathways Simulation System (RenpassG!S)
Renewable energy rider (RER)
Renewable energy system (RES)
Small Island Developing States (SIDS)
Small Island Developing (SID)
Sustainable Development Goals (SDGs)
Sustainable Energy Framework (SEF)
Total energy supply (TES)
United Nations Development Programmes (UNDP)
United Nations Environmental Programme (UNEP)
United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States (UN-OHRLLS)
Variable renewable energy sources (VRES)
Vehicle to grid (V2G)
World Wildlife Fund (WWF)
Bukley Bagasse Plant (bagasse-Bukley)
Andrews Bagasse Plant (bagasse-Andrew)
Portland Bagasse Plant (bagasse-Portland)

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Chapter 1 – Purpose of thesis

1.1. Outline of Problem

Scientific literature supports that climate change is potentially the greatest global calamity for present and future generations. Ultimately, the international community of developed nations sought to mitigate the most detrimental impacts through global agreements by which signatory nations committed to reducing greenhouse gas emissions in the atmosphere. The first significant global commitment started with the Kyoto Protocol which required developed nations to reduce greenhouse gas emissions (United Nations 2023). However, the Paris Agreement was created to specifically ensure that the global average temperature rise this century below 2 degrees above pre-industrial levels and to purse efforts to limit the temperature increase further to 1.5 degrees Celsius (Teske 2019). More importantly, all groups nations were asked to reduce emissions, through national determined contributions that requires all nations regularly report on emissions targets and implementation efforts. As a result, new concepts to completely changing energy systems from fossil fuel dependence became more prevalent to national and international discussions. Consequently, several studies (Hansen, Breyer, and Lund 2019; Mathiesen, Lund, and Karlsson 2011; Child et al. 2019) attribute the emergence of a 100% renewable energy system (RES) to early efforts to mitigate climate change by reducing greenhouse gas emissions from fossil fuels with cleaner renewable energy sources.

Transitioning to higher shares of renewables significantly reduces greenhouse gas emissions, as the energy sector accounts for 75% of total global carbon dioxide emissions (Manish, Pillai, and Banerjee 2006). Globally increasing the share of renewables also coincides with goal 17 of the United Nations Sustainable Development Goals (SDGs) by 2030, which *constitutes* – "ensuring affordable, reliable, and clean energy for all and sustainably increasing the share of renewable energy in the global energy mix by 2030" (General Assembly 2015). The cost competitiveness of renewables has significantly improved compared to fossil fuel resources. Since 2018 renewables have become the lowest-cost source for power generation, with the costs of wind and photovoltaic technologies projected to continue declining in the following years (IRENA 2019, 10).

Since 2009, solar PV modules have declined in price by 30 - 40%. Furthermore, the global weighted average electricity cost for solar photovoltaics has fallen within fossil fuel costs (IRENA 2020a). In addition, between 2016 and 2018, the global average costs of wind declined from USD 76 /MWh to USD 53 /MWh, with the Levelized Cost of Energy (LCOE) for new onshore wind expected to further decline by 15% between 2020 - 2025 (IEA 2021). By 2020, without financial assistance, onshore wind and solar PV are expected to be cheaper than the least-cost fossil fuel alternative (IRENA 2019, 9). As the cost-competitiveness of various renewable energy technologies for electricity generation has been proven, global acceptance of renewable energy technologies has also significantly improved (Griffiths 2017). In the long-term, the argument for more renewables makes logical sense as fossil fuel reserves are declining, and other sources of energy, such as nuclear power, are expensive and contribute to compromising global security (Owen, Inderwildi, and King 2010; Singer, Denruyter, and Yener 2017).

However, most of the research in academia on 100% RE systems was on the national level, followed by fewer studies conducted on a regional or global scale (Hansen, Breyer, and Lund 2019, 773–74). Numerous publications were focused on EU nations and surrounding regions: Denmark, Ireland, England, Germany, Spain, and Macedonia. Although, within the past five years, there was an increase in both qualitative and quantitative publications regarding a 100% RES that focused on developing nations, individual islands, or groups of islands such as the following: Reunion Island, Flores Island, Aland Islands, Korčula, Gran Canaria, Canary Islands, Fiji, Mauritius, Canarias Archipelago, Philippines Pico and Faial. In the case of quantitative investigations, these were conducted using commercially available closed energy system models (ESMS). Therefore, literature shows publications on insular island systems, but few publications were found to date that focused explicitly on the English-speaking Caribbean nations as SIDS, which is further explained in Chapter 3, specifically Barbados, that utilized open-source code or tools as the primary modelling framework. Therefore, this investigation and research are new in academia.

1.2. Research Rationale

This research uses Barbados as a model to examine the transition towards an energy system with 100% RE electricity in SIDS. However, as other SIDS, Barbados is dependent on and influenced significantly by international aid agencies that conduct and fund most future studies as a requirement for policy-based loans. The research proposes an open and transparent energy system modelling framework to enhance the policy planning process, as the energy system model's methodology, mathematical approach, and structure (ESM) are open. Consequently, all stakeholders can quickly critique the scenario analysis results, enabling more transparent and open dialogues regarding the findings.

Based on the “openmod philosophy,” oemof and PyPSA were proposed as modelling tools to conduct scenario analysis to examine possible futures for the Barbadian energy system. The future energy system must be technically and economically sound in these scenarios. The load must meet the demand at every time step without failure. Therefore, the investigation must be conducted at a high spatial and temporal resolution. The investigation must also simulate all renewable energy generators, storage technologies, conventional gensets, and the interactions among critical energy-consuming sectors such as tourism and transportation. Ultimately, the investigation is not intended to argue with present or past policy decisions but instead use the "openmod philosophy" to produce transparent and open scenarios for all stakeholders in the energy sector to critique and discuss possible futures for the Barbadian energy system. Regarding research findings, it is not an issue of "right or wrong," instead, based on the findings, what are the best options for Barbados. More importantly, to provide a platform for open dialogue regarding analytical results on possible futures for the Barbadian energy system.

1.3. Research Questions

The final 100% RES will be considerably different from the current energy system due to significant changes in the generation and transmission of electrical power on the grid. Therefore, the modelling must also include an electricity grid model for examining the relationship between the flow of current and voltage on the power grid to determine the scale of grid expansion that accommodates significant variable renewable energy electricity. Based on the intention of the GoB to pursue a 100% RES four main research questions were formulated as follows:

1. Are open-source modelling tools suitable for conducting scenario analysis of a 100% RES for Barbados?
2. What are most significant renewable resources required to attain a 100% RES for Barbados?
3. Does the north of the island require the most significant grid expansion to accommodate higher shares of renewable energy?
4. Can the power grid of Barbados take a 100% RES with some reinforcement?

Based on these main research goals, the research was summarised in Figure 1.1. Notwithstanding, the literature review was structured, as shown in Figure 1.2 to highlight the allocation of the different parts of the work to different phases of the research.

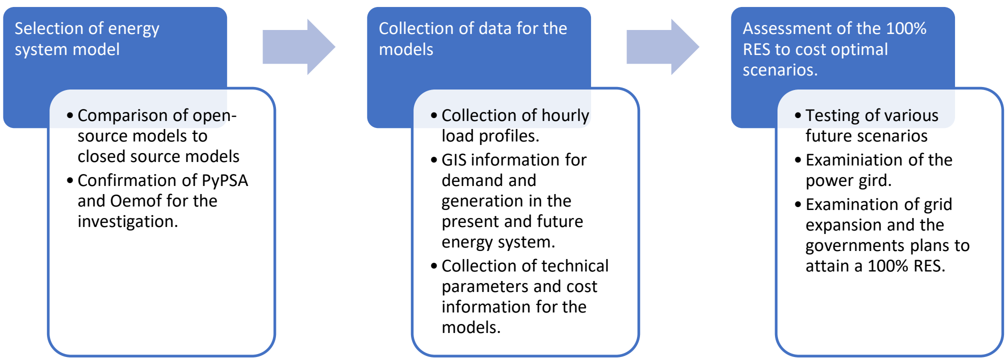

Figure 1.1. The technical assessment of the 100% renewable energy system for Barbados.

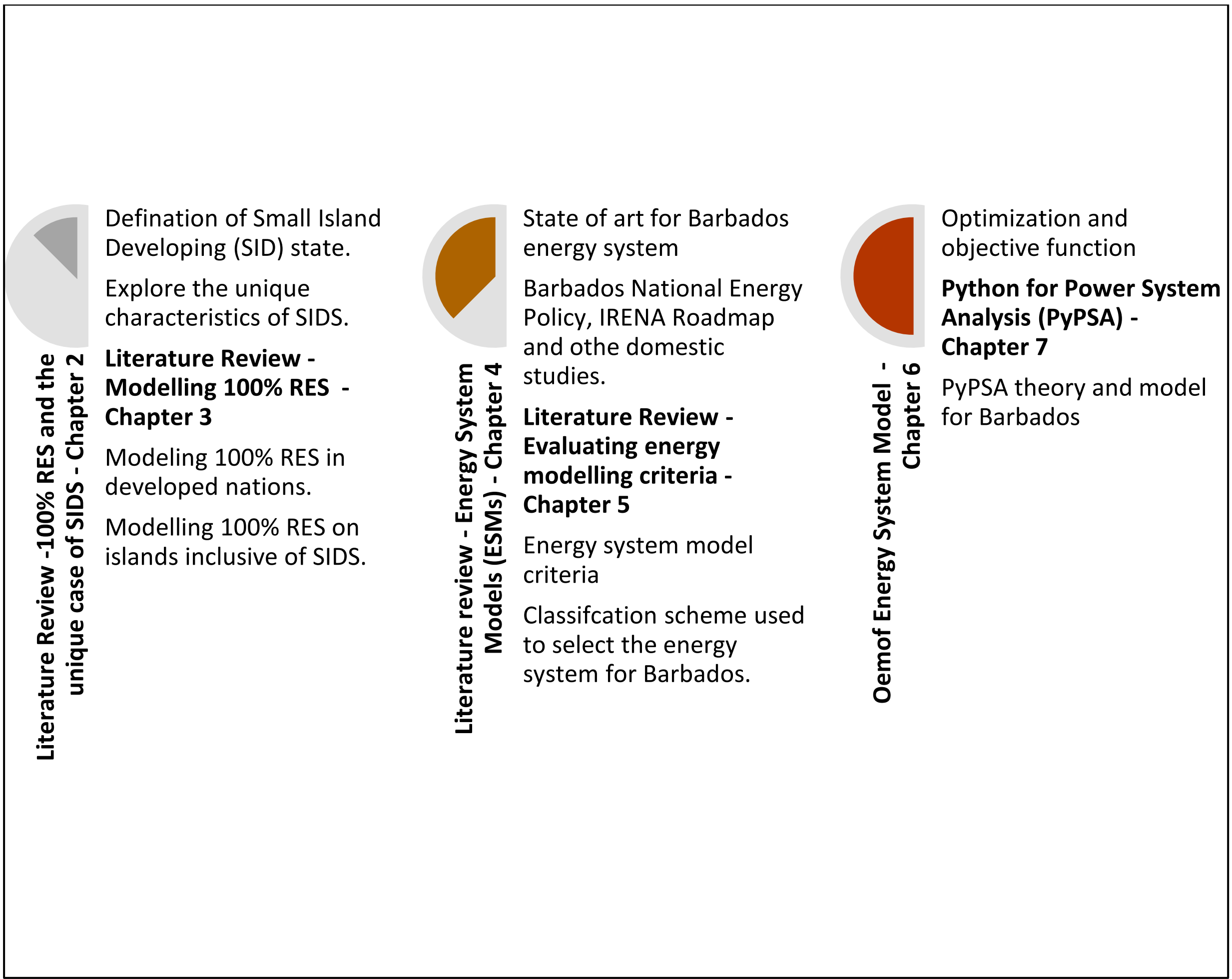

Figure 1.2. Summarizes the structure of the literature review.

1.4. Methodology

This research examines the transition towards an energy system with 100% RE electricity in SIDS, using Barbados as an example. Specifically, this investigation focuses on using open source/access energy system models (ESMS) for analysis to increase transparency in the policy planning process as the methodology, mathematical approach, output data, and model structure is open. Based on the "openmod philosophy," oemof and PyPSA were proposed as modelling tools to conduct scenario analysis to examine possible futures for the Barbadian energy system. Consequently, all stakeholders can quickly critique the scenario analysis results, enabling more transparent and open dialogues regarding the findings.

As other SID states, Barbados is dependent and influenced significantly by international external aid agencies that either conduct or fund most of the energy system analysis or future studies as a requirement for policy-based financing. However, most investigations in the literature on scenario analysis or energy system modelling were conducted using closed commercial black-box ESMS. However, these models are not best suited for building stakeholder trust, as the model structure, output data, methodologies and mathematical approach are unavailable for third-party examination. In many cases even the national utility companies of respective SIDS do not have the full transparency after the modelling, which is mostly done by outside consultants. Several closed ESMS in the literature were examined to develop a classification scheme to compare these to the open-source ESMS considered for this investigation.

The future 100% RE system must be technically and economically sound in these scenarios. Therefore, the load must meet the demand at every time step without failure. Consequently, the investigation must be conducted at high spatial and temporal resolution. The investigation must also simulate all renewable energy generators, storage technologies, conventional gensets, and the interactions among critical energy-consuming sectors such as tourism and transportation. Ultimately, the investigation is not intended to argue with present or past policy decisions but instead, use the "openmod philosophy" to produce transparent and open scenarios for all stakeholders in the energy sector to openly critique and discuss possible futures for the Barbadian energy system. Regarding research findings, it is not an issue of "right or wrong" Rather, based on the findings, what are the best options for the Barbadian energy system.

1.5. Sensitivity Analysis

In the case of the oemof-barbados model, sensitivity analysis was conducted in various scenarios that analyzed changing cost and technical parameters such as renewable energy resource potentials or cost in addition to various flexible generation options.

Chapter 2 – The unique situation of SIDS

2.1. Definition of Small Island Developing States (SIDS)

The UN-OHRLLS (2017) defines SIDS as a distinct group of developing nations that face unique social, economic, and environmental vulnerabilities. These islands are primarily located in three geographical locations: the Caribbean, the Pacific and Atlantic; Indian Ocean, Mediterranean and South China Sea (AIMS), as listed in Table 2.1 below (UN-OHRLLS 2011).

Table 2.1. Summaries a complete list of SIDS around the world (UN-OHRLLS 2011)

Regions	**Nations**	
Caribbean and Latin America	Anguilla	Guyana
	Antigua and Barbuda	Haiti*
	Aruba	Jamaica
	Bahamas	Martinique
	Barbados	Montserrat
	Belize	Puerto Rico
	Bermuda	Sint Maarten
	Belize	St. Kitts and Nevis
	Bermuda	St. Lucia
	The British Virgin Islands	St. Vincent and the Grenadines
	Cayman Islands	Suriname
	Cuba	Trinidad and Tobago
	Curacao	Turks and Caicos Islands
	Dominica	United States Virgin Islands
	Dominican Republic	
	Grenada	
	Guadeloupe	
Pacific Islands and AIMS	Tonga	Mauritius
	Singapore	Fiji
	Seychelles	Guinea-Bissau*
	The Solomon Islands*	Cabo Verde

Regions	Nations	
	Tuvalu*	Bahrain
	Vanuatu	Maldives
	Federated States of Micronesia	Marshall Islands
	Palau	Samoa
	Kiribati*	São Tomé and Principe
	Timor-Leste*	Comoros*

Typically, land area, population, and economic and environmental characteristics have been used to define SIDS in the literature (Pelling and Uitto 2001). Briguglio (1995) describes several common characteristics of all SIDS, including Barbados, which makes SIDS an exceptional case for environmental challenges and economic development. These serve to directly and indirectly compromise the socio-economic survival and ability to invest in sustainable development (Surroop, Raghoo, and Bundhoo 2018; Wolf et al. 2016; Niles and Lloyd 2013; Niles 2013). These characteristics of SIDS vary in literature but can be summarised as follows: price takers in international trade of fossil fuels; limited sources of foreign exchange and sources of income; debt accumulation and dependence on external aid agencies, and susceptibility to external occurrences.

2.1.1. Price-takers in the international trade of fossil fuels

Most literature supports that SIDS are price-takers in international trade and are heavily dependent on expensive imported fossil fuels for power generation and transportation (Surroop, Raghoo, and Bundhoo 2018, 46–47; Wolf et al. 2016, 2–3; Briguglio 1995, 1616–17). Heavy reliance on fossil fuel imports for electricity and transportation has afforded these nations significant economic growth and social development for several decades. The heavy exploitation of fossil fuels continued uninterrupted in SIDS as for the rest of the world until the first oil crisis of 1973. Niles and Lloyd (2013, 524) argued that most SIDS could not negotiate discounted fossil fuel prices due to their limited demand. Many experienced varying degrees of geographical isolation from neighbouring islands or larger nations, which meant they were not on major transportation routes and experienced higher transport premiums.

Furthermore, the inability to trade in electricity with contiguous states also remains an essential factor that inflates the price of electrical power on the most remote islands. These events prioritized transitioning from fossil fuel dependence to renewables only when the price of oil was high (Niles 2013, 524; Haynes 2015). However, as observed in the 1980s, most interests in renewable energy technologies subsided once the oil price plummeted. In the Pacific Islands and Archipelago, biomass and hydropower were the only renewable energy sources utilized in some limited cases. A similar trend was observed in Barbados. Haynes (Haynes 2015) noted, as oil prices plummeted, the demand for renewables dwindled. However, starting from a very low level, between 2002 to 2010, the high price of imported oil increased, fuelling interest from public and private sector energy stakeholders to pursue renewable energy, as indicated by a sharp increase in the number of solar PV installations.

Following 2010, interest in renewable energy in the private sector and general public has been maintained, especially as renewables became increasingly cost-competitive with fossil fuel alternatives. Also, for successive Government administrations, the volatility of international fossil fuel resources has been a significant drain on foreign reserves (Lorde, Waithe, and Francis 2010; Downes et al. 2017). Barbados has experienced several macro-economic challenges due to the global financial crisis, particularly, the declining competitiveness of foreign earning sectors such as tourism (Haynes 2015; 2023). The economic situation of SIDS globally was also further compromised by the Covid-19 pandemic as economic recovery is expected to take several years (Kim 2020). Consequently, transitioning from dependence on volatile fossil fuel resources to save foreign exchange remains a national priority for policy makers (Downes et al. 2017, 3–5; Haynes 2023). Simply put - the transition to a 100% renewable energy system “makes economic sense” and was adopted as a national policy goal by successive Government administrations and with keen interest from energy sector stakeholders.

2.1.2. Limited sources of foreign exchange and sources of income

SIDS are generally characterized by small market size, limited domestic manufacturing capabilities and dependence on a narrow range of products for foreign exchange. In the Pacific islands, the higher oil prices increased the exportation of cash crops and timber, which is a potential cause of future ecological and environmental problems (Niles and Lloyd 2013, 521–22). In Barbados, the island has limited natural resources for export, limited market size, and heavy dependence on tourism for foreign exchange (Barbados Society of Technologists in Agriculture 2010; Lorde, Francis, and Drakes 2011). Specifically, the primary source of foreign exchange is tourism, with some lingering dependence on the sugar industry at a loss to the agricultural industry, with direct taxation being one of the largest sources of revenue for the government (Lorde, Francis, and Drakes 2011; Barbados Society of Technologists in Agriculture 2010; Wyllie, Essah, and Ofetotse 2018). Presently, the tourism industry is the primary foreign exchange and economic development source. From 2017 to 2018, cruise-ship passengers generated $71 million US dollars, contributing to direct and indirect wage incomes of $14.09 million US dollars and $25.36 million US dollars. The sugar industry still contributes to foreign exchange. However, as the final product is worth less than half the production costs when sold on international markets, this is a loss to the agricultural industry (Daly and Fernandez-Stark 2017).

2.1.3. Susceptibility to external occurrences

To further compound the plight of SIDS in achieving sustainable development, these nations are also vulnerable to external factors that compromise economic development (Niles and Lloyd 2013, 525–26; Niles 2013). Tourism is the primary economic sector for the Caribbean and Pacific SIDS (Lorde, Francis, and Drakes 2011). However, external occurrences in the post-2008 Global Financial Crisis negatively affected tourism source markets and trade partners in developed nations (Hinds and Stephen 2017). Eventually, the Barbadian economy became 5% smaller, with an economic deficit of 15% in 2014. This external occurrence compromised economic development and the ability of the nation to invest in sustainable development with domestic sources of funding, making many SIDS more dependent on donor and funding agencies (Haynes 2021b).

Furthermore, following the COVID-19 pandemic, SIDS heavily reliant on air or sea tourism industries were severely impacted by the global pandemic, experiencing an almost 99% reduction in visitor arrivals (Leal Filho et al. 2020). The size and duration of the economic shock may vary for each SID state. However, as most SIDS, including Barbados, have not even recovered from the 2008 global economic crisis, recovery rates of 5 years or longer from the effects of the Corona pandemic can be expected with negative impacts on domestic spending on sustainable development programmes (Kim 2020; UN-OHRLIS 2021).

2.1.4. Dept accumulation and dependence on external aid agencies

An increasing and volatile price for imported fossil fuels is a significant cause of severe debt accumulation among SIDS; in some cases, nations cannot meet the costs of oil imports (Niles and Lloyd 2013, 525–26). Barbados has always experienced debt due to a continuous imbalance in total government expenditure and revenues (Hinds and Stephen 2017). Consequently, shortfalls are met with funding from donor or loan agencies. In the case of the Pacific Islands, the International Monetary Fund (IMF) showed that several nations could completely deplete foreign reserves in a few weeks in the cases of consistently high oil prices (Niles and Lloyd 2013, 526).

In analysing groups of SIDS Niles (2013, 528) argued that sustainable development is limited to the financial resources of the SID state and the ability to access donor funding as part of the acquisition process for new power generation technologies. In comparison to SIDS in the Pacific, Barbados and other Caribbean SIDS have benefited from funding from donor agencies for policy-based loans or grants, specifically in the following areas: to provide institutional and technical capacity building; to afford grid expansion and other high-cost energy infrastructure; to purchase large-scale fossil fuel-based generators. Interestingly, most of the aid used for renewable energy-based projects was as follows: large-scale hydropower project (15%), followed by bioenergy (1%), wind (1%) and solar (0%). Donor agencies often have the technical, legal, and professional services required to draft policies or review institutional structures (Niles and Lloyd 2013, 528). The authors also argue that in some cases, energy policy development is a prerequisite or condition to further to access funds from the donor or loan agency. The rationale is that the written policy indicates political will and provides a clear legislative framework to facilitate investment in the sector.

In 2010, in collaboration with IADB, the GoB drafted the Sustainable Energy Framework for Barbados (GOB, Stantec, and Castalia 2010) as the policy prerequisite for funding from the Inter-American Development Bank (IADB) in the form of the Sustainable Investment Programme (Energy Smart Fund I), which Energy Smart Fund II followed to support technical capacity building, technical assistance for renewable energy and energy efficiency projects (GOB 2023).

In the case of Barbados, about 85 MW of renewable energy in distributed solar PV and 10 MW of utility scale solar PV are connected to the power grid, with an estimated 90 MW in the planning phase or pending connection approval. The vast majority of renewable energy in the form of solar PV is 12% of the electricity generation mix that local investors financed. This fact supports local investors' strong interest and financial capacity in advancing renewable energy development in Barbados, especially Solar PV (Haynes 2023). The first significant challenge in expanding renewable energy was the need for a stable economic and financial environment to support renewables in the energy market. Around 2010, the government implemented the renewable energy rider (RER) programme to incentivise the installation of RE by compensating renewable energy electricity producers based on a rate linked to the fuel cost adjustment (FCA) paid for fossil fuel imports. Consequently, the remuneration rate for renewables declined with the drop in price of imported fossil fuels for electricity generation (Haynes 2015; GOB, Stantec, and Castalia 2010). Following the implementation of the Electricity Market Study as advised by Hohmeyer (2017, 82), the country was advised on the best economic tools and Feed-in-Tariff (FIT) structure for supporting various forms of renewable electricity (GOB 2019; Hohmeyer 2017; Haynes 2023). With the implementation of a stable FIT, the number of installations has increased as the total investments in the renewable energy sector in particular solar PV is over 100 Million BBDS (Haynes 2023). Among other issues that limit the expansion of renewable energy are challenges in attaining grid connection and some cases planning permission (Haynes 2023).

Conclusion

Transitioning to higher shares of renewable energy is vital for economic survival, but SIDS have unique economic and fiscal challenges compared to developed nation counterparts. In particular, their unique characteristics and vulnerabilities compromise their capacity to invest in sustainable development. In the case of Barbados, the nation has benefited from funding from donor agencies. However, the bulk of investment in renewable energy projects, in the form of solar PV, has been generated by local investors. Nonetheless, the island is still experiencing challenges in achieving higher shares of renewable energy, as evident in the recent stall in approval for new solar PV applications for grid connection. The Barbados case highlights the need for research and detailed studies regarding the unique position of SIDS regarding energy sector transformation within the economic, market and technical constraints.

Chapter 3 – A 100% renewable energy system – A new paradigm for SIDS and the developing world

3.1. 100% Renewable Energy Systems in Literature

The primary sources of literature specific to the topic of a 100% RES included academia and significant reports from global agencies involved in funding sustainable development as follows: The United Nations Development Programmes (UNDP), United Nations Environmental Programme (UNEP), World Wildlife Fund (WWF), International Renewable Energy Agency (IRENA), or the US National Renewable Energy Laboratory (NREL). These global agencies have a critical role in funding sustainable development, including renewable energy development in SIDS. These consistently have information regarding the concept that may be unexplored in academia. Nonetheless, academic literature was researched for the past 15 years using mainly online sources such as Google Scholar, ResearchGate and Elsevier Journal database, to name a few. The search focused on a "100% renewable energy system (RES)" and other current topics in energy system modelling specifically. As Barbados is a SID state, the "100% renewable energy system in SIDS" was researched. As SIDS are a class of developing nation, the search was expanded to include - "100% RES in developing nations". Furthermore, as SIDS are island nations, the search also examined - "100% RES for insular or island energy systems". The literature search was also expanded to include "energy modelling tools for modelling high shares of variable renewable energy sources (VRES) such as intermittent wind and solar power" for the previously mentioned category of nations, based on the research criteria.

3.2. Definition of a 100% Renewable Energy System

The 100% RES represents a radical change in traditional fossil fuel-powered energy systems. The terminology changes in literature ranging from "100% renewable energy systems (RES)" "100% renewables" or "100% renewable energy (RE)" (Hansen, Breyer, and Lund 2019). Droege (2012) defines the transition to a 100% RES as a collective choice to change the energy sector from a high degree of fossil fuel dependence to an entirely renewable energy power base. However, as noted by Hansen et al. (2019, 472–73), there is no true formal definition of the term; some studies have focused on the electricity sector, whereas other studies focused on the entire energy system, inclusive of heating or cooling, transportation, and industrial sectors. This research also contends that since 2019 there has been growing interest in the topic. In 2009, few studies were published, which increased to 15 studies by 2014. The publications peaked in 2017 and 2018, with more than 40 studies recorded. Therefore, as noted by the UN Environmental Programme (2020), 100% RE system is gaining momentum internationally, with more than 250 cities aiming for 100% RE systems in the form of electricity generation, heating, cooling, and transportation.

Furthermore, the IRENA Coalition for Action (2019) noted that as recent as 2018, 53 new countries have committed to various policy targets to achieve a 100% RES. Pursuing a 100% RES is also a goal of several companies and utilities; many have formulated a 100% RES target. For example, electric utilities in India, Spain, and the United States now target zero emissions by eliminating coal-fired plants or transitioning to 100% renewable energy (UN Environment Programme and Secretariat 2020, 30–31). In recognizing the inevitable transition to higher shares of renewables, several utilities throughout Europe are reshuffling operations and plant dispatch to accommodate increasing shares of low-cost wind and solar electricity on the power grid.

3.3. Modelling of a 100% renewable energy system in developed nations

Initially, most of the research on 100% RE systems was conducted for developed nations, the main findings, and the type of energy modelling tools used from a sample of publications are summarized in Table 3.1 below. Faulstich et al. (2011) detailed the pathway to a 100% renewable energy system for Germany. The report highlights several relevant concepts for planning a 100% renewable energy system, which was also concurred in the other reports mentioned in Table 3.1 below. For example, for a 100% RES, the main aim is ensuring electricity demand meets the demand at all time intervals, particularly by covering the resulting electricity demand that renewables cannot cover, otherwise referred to as the “residual load”, to maintain reliable electricity and grid stability. The concept highlights that large base load power plants are mainly incompatible in an energy system with high shares of variable renewable resources rather the 100% RES will require energy storage, dispatchable power stations, demand side management (DSM) and wide area transmission networks in balancing the intermittency from renewable resources.

Several advantages are observed in investigating a 100% RES in developed nations. These nations benefit significantly from having larger geographical sizes to exploit accessibility to more flexible renewable resources such as biomass or interconnected power grids with neighbouring regions to account for shortfalls in satisfying the demand, as seen in the case of Denmark (Lund and Mathiesen 2009). The analysis of a 100% RES for Ireland highlighted the importance of cross-sectoral analysis to examine the interconnectedness of the power sector to other energy sectors such as transportation, heating, and cooling (Connolly et al. 2011). In addition, Denmark and Macedonia could also exploit high biomass potentials as a form of energy fuel and storage to attain 100% RE systems as opposed to high dependence on wind energy, which would require ample electrical or hydrogen storage (Ćosić, Krajačić, and Duić 2012; Lund and Mathiesen 2009). In particular, Korberg et al. (2020) highlighted the beneficial role of integrating biomass as a feedstock for biogas production even in an energy system dominated by wind and solar to produce 85% of the electricity in the Danish power system. Some investigations showed that a 100% RES was technically feasible, but it was not necessarily the optimal energy mix, as such was the case for Macedonia (Ćosić, Krajačić, and Duić 2012, 80). Specifically, a 50% RES with energy efficiency measures to decrease consumption and install new generation units was more probable than the 100% RES. The research showed that the final 100% RES was highly dependent on new storage technologies in the form of heat-pumps to compensate for the intermittency of VRES and to decrease the excess electricity production, which would otherwise cause an increase in the wind power capacity, referred as the critical excess of the electricity production (CEEP).

Table 3.1.Summarizing a 100% RES in developed countries and the energy modelling tools used in the investigations.

Study.	**Main findings**	**Energy model**
(Germany) Pathways towards a 100 % renewable electricity system (Faulstich et al. 2011).	• *According to the study, a renewable-based energy system would require fewer baseload power plants, while relying more on flexible conventional sources such as gas rather than coal.* • *The scenarios showed that provided the required storage facilities and grid were implemented, an entirely renewable electricity supply that was as reliable and affordable as possible for Germany.* • *Exploiting the EU internal market, energy was recommended for importing electricity. For example, a Germany-Denmark-Norway energy network would allow for the use of substantial Scandinavian pump storage capacity in particular to exploiting offshore wind power capacity in the North Sea region.*	REMix
(Denmark) Energy system analysis of 100% renewable energy systems— The case of Denmark in the years 2030 and 2050 (Lund and Mathiesen 2009)	• The 100% RES for Denmark was deemed possible using domestic renewable energy resources. However, the pathway depends on utilizing the biomass resource that competes with agriculture. The utilization of the wind energy potential is a possibility that will require a large share of hydrogen storage, which resulted in higher system energy losses.	EnergyPLAN
(Denmark) The role of biogas and biogas-derived fuels in a 100% renewable energy system in Denmark (Korberg, Skov, and Mathiesen 2020)	• Utilizing biogas for energy production creates significant savings when the biogas feedstock is free. • The savings from using biogas are reduced when the sector pays for the feedstock, but these are still cost-competitive. • Liquid bio-electro fuels for transport with biomethane show slight cost reductions in the model but higher costs when using electro methane. • Electro methane is economically unfeasible for power, heat, industry and partly transportation, independent of the dry biomass costs.	EnergyPLAN
(Ireland) The first step towards a 100% renewable energy system for Ireland (Connolly et al. 2011)	• A 100% RES for Ireland was possible based on several assumptions used to create the model, but these will require additional studies to corroborated on the main findings. • The integration of all three sectors, heat, transportation, and electricity, was required to achieve 100% RES.	EnergyPLAN
(Macedonia) A 100% renewable energy system in	• The results showed that a 100% renewable energy system in Macedonia is possible; however, a high share of biomass, wind power and solar power, and different storage technologies were	EnergyPLAN

Study.	Main findings	Energy model
the year 2050: The case of Macedonia (Ćosić, Krajačić, and Duić 2012)	needed to achieve this goal.[1]	

3.4. Modelling a 100% RES in developing nations, SIDS, and other insular systems

An even smaller number of studies focused on developing nations, let alone SIDS; notwithstanding, the number of studies on these topics has increased within the last five years. However, the literature did not always clarify the distinction between SIDS, developing nations, and insular island systems. Some of the island nations mentioned in the literature included the following: Reunion Island, Flores Island, Porto Santo, Aland Islands, Korčula, Gran Canaria, Canary Islands, Canarias Archipelago, Pico and Faial, Philippines, with the islands of Fiji, Mauritius, Cook Islands, and the Marshall Islands being SIDS. Equally as important is the variation in traits for island nations in the following: population size, renewable energy potentials, natural resources, and economic and technical constraints. In several of these studies, the main findings, energy modelling tools and critical statistics are summarized in Table 3.2 below.

Table 3.2. Summarizing investigations conducted in insular energy systems and SIDS.

Study	Main findings	Energy model	Peak load (MW)	Installed capacity (MW)	Population
Pico and Faial in the Azores: On the road to 100% renewable energy systems in isolated islands (Alves, Segurado, and Costa 2020)	• Pico and Faial's islands in the Azores can significantly increase RE penetration with lower costs. However, the interconnection of the islands is the only solution that allows for the complete elimination of fossil fuel use on both islands.	EnergyPLAN	65 (2020)	160 (2020)	140,000 (2020)
Reunion Island: The renewable energy revolution of Reunion Island	• About 50% of the electricity generation from biomass is possible due to its economic viability.	TIMES Model	493 (2018)	843.9 (2018)	450,000 – 837,900) (2018)

[1] The citations for the reports analyzed in Table 3.2 were listed with the studies mentioned as shown in above.

Study	Main findings	Energy model	Peak load (MW)	Installed capacity (MW)	Population
(Selosse et al. 2018) **(Maïzi et al. 2018)** **(Guezello 2018)**					
Porto Santo: Increasing renewable energy sources in island energy supply: case study Porto Santo (Ćosić, Krajačić, and Duić 2012) **(Torabi et al. 2020)**	• A 100% RES for Porto Santo Island is possible with 2-weeks of hydrogen storage to improve the utilization rate of the wind resource by compensating for the variable nature of the wind.	H2RES model	125-135 (2012)	16 (thermal plants) (2012) 1.11 (2012) (wind), 2.34 (2012) (solar)	5,500 - 20,000 (2012) (Varies with tourism arrivals)
Åland Islands - Archipelago: Scenarios for a sustainable energy system in the Åland Islands in 2030 (Child, Nordling, and Breyer 2017)	• 100% RE-based domestic production can be achieved with or without reliance on imported energy by integrating V2G connections with power-to-gas technologies. • V2G batteries were shown to provide 100% electricity storage. • A highly electrified transport sector can support the 100% RES and lower annualized energy system costs.	EnergyPLAN	N/A	N/A	N/A
Mauritius: Exploring options for a 100% renewable energy system in Mauritius by 2050 (Khoodaruth et al. 2017)	• The authors examined various energy mixes to attain a 100% RES. • Solar PV, solar thermal, onshore, offshore wind and bagasse gasification were recognized as the most utilized resources. • Consequently, the deployment of smart grids to facilitate the integration of various RE technologies was recommended, in addition to substantial investments into financial resources and subsidies to support the transition.	No ESM.	N/A	N/A	N/A

Study	Main findings	Energy model	Peak load (MW)	Installed capacity (MW)	Population
Gran Canaria: Smart renewable energy penetration strategies on islands: The case of Gran Canaria (Cabrera, Lund, and Carta 2018) **(Perez and Ramos Real 2008)**	• A cross-sectional approach was considered with incorporated electricity, heating/ cooling, desalination, transport, and gas. • A proposed 75.9% RES using mature technologies and strategies can be implemented. • The 100% RES can be reached with integration with the improved maturity of some technology's storage technologies (i.e., smart charging)	EnergyPlan	552 (2008)	860 (2008)	840,000 (2008)
La Gomera: 100% RES: **Assessment of sustainable energy system configuration for a small Canary Island in 2030 (Meschede, Child, and Breyer 2018)** **(Ramos-Real et al. 2018)**	• 100% RES for island Gomera is technically and economically feasible. • Solar PV and battery storage are the best options for an island comparable to Gomera. • The analysis underlines that the combination of different technologies will lead to the lowest primary energy demand and the lowest annualized cost of 10.89 M€ • Fossil fuel-powered plants were used in modelling the energy system design. An energy system without conventional power plants can be examined, but that would lead to higher annual costs than those using the power plants to cover only the peak demands.	EnergyPLAN	12.3 (2018)	22.9 (2018)	21,503 (2018)
La Gomera, Gran Canaria North and South: Carbon neutral Archipelago – 100% renewable energy supply for the Canary Islands (H. C. Gils and Simon 2017)	• The pathway to 100% RES was modelled, combining a bottom-up energy accounting framework Mesap-PlaNet and REMix optimization power system model. • A backcasting approach was used, and a series of long-term to short-term actions. • The flexible operation of BEV charging, hydrogen electrolysis, reverse osmosis seawater facilities, and other energy sectors are critical to achieving high RE shares. • Load shifting of BEV, heating, cooling, and desalination provided cheaper storage options than	Map-PlaNet REMix	N/A	N/A	N/A

Study	Main findings	Energy model	Peak load (MW)	Installed capacity (MW)	Population
	electric traditional energy storage. • The small size and islands' insularity make implementing biomass and hydropower challenging; therefore, electrifying the transport and heating sectors were viable options to achieve higher shares of renewables.				
Korčula island: Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources (Dorotić et al. 2019) **(Pfeifer, Prebeg, and Duić 2020)**	• The authors examined a 100% RES with renewables and V2G for demand response. • An optimal RES with interconnection to the mainland is possible for Korčula.	EnergyPLAN	_	58,289 (2016)	15,522 (2016)
Aruba: Integrated energy planning with a high share of variable renewable energy sources for a Caribbean Island (Dominković et al. 2018) **(National Renewable Energy Laboratory 2020)**	• A 78.1% share of renewables in the electricity mix of Aruba was the optimal energy system with a 2.5% reduction in system costs inclusive of CO2emissions compared to the current fossil fuel-based system.	PLEXUS	135 (2019)	287.9 (2020)	105,845 (2020)
Jamaica: Photurgen: The open-source software for the analysis and design of hybrid solar	• Open-source research. • An open-access/source model and GIS information to optimize hybrid solar-wind systems on the island of Jamaica.	Photurgen	644.4 (2015)	923 (2015)	2,930,050 (2015)

Study	Main findings	Energy model	Peak load (MW)	Installed capacity (MW)	Population
wind energy systems in the Caribbean region: A brief introduction to its development policy (Watson et al. 2017)					
Jamaica: Pathways to climate change mitigation and stable energy by 100% renewable for a small island: Jamaica as an example (Chen et al. 2020)	• A 100% renewable energy system was possible for the island of Jamaica by replacing spinning reserves from fossil fuel plants with battery energy storage.	DIgSILENT/ Power Factory	–	–	–
Cuba: Energy System Planning towards Renewable Power System: Energy Matrix Change in Cuba by 2030 (Vazquez et al. 2018). **(OAS 2016)** **(López and Berdellans 2002)**[2]	• Future studies were conducted to examine various scenarios of a 100% RES to estimate the level of investment and possible final dispatch options.	LINDA-spreadsheet-based model	2,199 MW (2006)	3,959.6 MW (2003)	11.3 (2003) Million

3.4.1. Energy System Characteristics of SIDS

In examining the studies in Table 3.2, despite having common economic characteristics, there is a significant variation in population, demographics, economic vulnerability, and renewable energy

[2] The citations for the reports analyzed in *Table 3.2* were listed with the studies mentioned as shown in above.

resource potentials among insular energy systems and SIDS. The analysis highlights unique solutions may be required for each state to transition to higher shares of renewables. For example, most SIDS are small nations except for Cuba, with a population of 11.3 million, in contrast to Niue, with 1,500 inhabitants; therefore, energy demands can vary with each nation (Henderson 2013). Surroop et al. (2018, 48–49) argued that the electrification rates vary with a rate of 100% in more advanced member states such as Singapore, Mauritius, or Barbados. At the same time, the electrification rate varies between groups of SIDS located in Africa, the Indian Ocean, the Mediterranean or South China Sea (AIMS), other Caribbean member states, and the Pacific Islands as 73-76%, 88.3% and 72.9%, respectively. The literature used peak power demand and annual energy consumption to classify islands as very-small islands (<1 MW and <2 GWh), small islands ([1-5MW] and [2-15 GWh]), medium islands ([5-35 MW] and [2-15 GWh]) and big islands (>35 MW and >100 GWh]) (Erdinc, Paterakis, and Catalão 2015). Power systems may comprise a single or few conventional fuel-based generators in very small and small island systems. However, with such a small number of generating units connected to the system, the inertia of the total system is considered critically low and vulnerable to significant frequency and voltage variation (Ratnam, Palanisamy, and Yang 2020; Ulbig, Borsche, and Andersson 2014). Typically, small to medium-sized island power systems are powered by diesel and heavy fuel oil units, which also have dynamic system operation that requires no operation below a certain threshold to avoid increased maintenance problems (Papathanassiou and Boulaxis 2006). Whereas, big islands, as seen in the case of Cuba, typically required extended generation such as steam turbines, and internal combustion, with combined cycle plants becoming more popular (Papathanassiou and Boulaxis 2006; Sigrist et al. 2016).

3.4.2. Renewable energy resource potentials in SIDS

Literature supports that most SIDS in the Caribbean, including Barbados, remain heavily dependent on imported fossil fuel resources despite high renewable energy potentials in solar and wind energy. However, there are notable exceptions, Trinidad and Tobago and Bahrain are exporters of fossil fuel resources and Belize imports 28% of electricity from Mexico. Suriname produces 45.9% from hydropower and 14.1% from biomass. Significant geothermal resources are found in St Vincent and St Lucia, with the possibility of interconnection between these nations and other select islands in the region to trade electricity.

In comparing the Pacific and the Caribbean regions, Blechinger et al. (2014) showed that the Caribbean region has the highest average electricity consumption, representing the highest market for extensive island energy systems. In addition, the Pacific region has the highest PV capacity, whereas, in the Atlantic Ocean, wind power exceeds the PV capacity five times for small islands. For island energy systems, hydropower, wind and solar are the main renewable-based contributors to power generation, with a few islands using biomass, geothermal and ocean power (Kuang et al. 2016).

However, in utilizing the wind potential, as seen in Porto Santo Island's case, the wind resource's variability critically reduced the renewable potential as a vital resource for attaining the 100% RES. In some cases, domestic biomass resource potentials were available at the required scale and reasonable economic costs to provide flexible power generation that accommodated VRES. Selosse et al. (2018) showed that for the Reunion Island, the high biomass resource was optimal for increasing the share of RE electricity, as the wind resource was limited by the occurrence of cyclonic winds known to devastate the region.

Furthermore, the island already benefited from hydropower, contributing 17.2% of the total electricity production, which added greatly to system grid stability. More importantly, the island is a French overseas territory that can benefit from technical and economic cooperation with France regarding transitioning to higher shares of renewables. As highlighted in the following sections, this is not the case for most English-speaking SIDS, especially in the Caribbean, making implementing renewables economically and institutionally challenging.

3.4.3. Island interconnection

Cross et al. (2017) concluded that the interconnection of islands improves overall cost efficiency and peak shaving through demand-side management and energy storage on islands with high renewable energy shares. In examining island energy systems in Pacific, Caribbean, and European territories, Kuang et al. (2016, 505) argued that in most cases, grid connection between adjacent islands or a larger mainland is not possible due to the high costs of submarine transmission cables. In investigating the Greek islands, the Islands of Pico and Faial, the Island of Korčula in Croatia and the Aland islands, these nations benefited from interconnection with the mainland or nearby territories. For the Aland Islands, high voltage interconnections to Sweden and Finland improved the security of supply and other challenges associated with the load satisfying the demand. However, energy system modelling showed that a 100% RES was possible with V2G services for electricity storage that reduced the need for imported electricity, seasonal storage, and synthetic fuel production from power to grid technologies and the installed capacity of offshore wind turbines (Child, Nordling, and Breyer 2017). However, for the island of Pico and Faial, interconnection was the only option for attaining a 100% share of renewables, and that scenario was the most expensive due to the costs associated with interconnection (Alves, Segurado, and Costa 2020).

3.4.4. Storage technologies

Storage options used in one situation may be unsuitable for another case. Blechinger et al. (2014, 328–29) and Child et al. (2017, 57) showed that without storage resources, the penetration of renewables is limited to 45.8%, whereas in utilizing storage, 70.9% of renewables may be installed. In exploring the cost-optimal electricity systems with increasing shares of renewables, Gioutsos et al. (2018, 437–38) showed that the levelized cost-optimal system (LCOS) for several islands usually occurred in the range of 40% - 80% renewable penetration rates. However, above this optimal range drawing closer to a 100% RES, the costs of the energy system increased due to the higher storage requirements to complement the higher shares of renewables. The authors further concluded that the high storage costs caused significant excess-production and the curtailment of renewables in the modelling, which was favoured over the implementation of more expensive storage technologies. The modelling also showed that for low-power demands, battery storage was preferred over pumped-hydro storage supporting renewable energy penetrations above the optimal range of 40% - 80%.

Blechinger et al. (2014) showed that subtropical regions, such as the Pacific and Indian oceans, which possessed high solar irradiation and low wind speeds that battery storage correlated best with PV by shifting the solar power from midday to the demand peaks in the evening hours, increasing the renewable shares from 40% - 50% and 60% - 70%. The research also showed that combinations of wind with battery storage were less favourable due to the higher variations of wind, which sometimes lasted weeks without energy production. Furthermore, seasonal storage was required to overcome periods of low wind speeds, as battery storage was unsuitable. Specifically, the installed battery capacity required to support the system was too high, becoming economically infeasible. Therefore, power-to-gas and pumped-hydro storage systems would be more economically feasible to support higher renewables shares during prolonged periods of low wind speeds. Kuang et al. (2016, 507–8) highlighted that hydropower generation can be operated flexibly and quickly and can thus be used for managing the variability of other renewable energy generators such as wind and solar. In addition, although both hydropower plants and pumped hydro-storage plants have high capital costs, operational and maintenance costs are typically low. However, regarding the island of Porto Santo, there were no significant hydropower or pumped hydro power resources available (Duić and Carvalho 2004, 387–88). However, two weeks of hydrogen storage was more promising to accommodate for the variation in the wind resource as there was no possibility of connection to the mainland power grid. Even with battery storage, only 45% of the demand could have been met due to the variable nature of the island's wind resource. Ultimately, a significant challenge to implementing pump hydro-storage is unfavourable geography, as was the case on several islands such as Samoa and Tuvalu (Kuang et al. 2016; Blechinger et al. 2014; Gioutsos et al. 2018).

3.4.5. Sector coupling and smart grid implementation

In particular, the modelling of island energy systems highlights the role of sector coupling to enable higher shares of renewables through the integration and incorporation of smart energy systems. In analyzing several island energy systems, smart energy systems were shown as credible options for improving the integration of renewable sources (Chen et al. 2020).

The smart grid facilitated real-time bidirectional communications regarding the VRES generation to customers and information on the electricity demand back to VRES generation units. Automated regulation of the demand to the supply is facilitated, thus enhancing stability and system reliability (Kuang et al. 2016, 509–11). The lack of mature, smart grid technology was one of the main limitations to implementing a 100% RES in Mauritius and Grand Canaria (Cabrera, Lund, and Carta 2018; Khoodaruth et al. 2017). Other viable options for smart energy integrations include vehicle to grid (V2G) and demand-side management (DSM), as highlighted in the case of the Canary, Korčula and Åland islands (Dorotić et al. 2019, 121–22). Child et al. (2017, 57) showed that V2G batteries play a crucial role in balancing supply and demand hourly, eliminating the need for seasonal storage in some cases and fewer offshore wind turbines.

Conclusion

The studies highlight significant variation regarding pathways to attain higher shares of renewable energy, specifically a 100% RES. There is no one-fit solution, as the variation among the SIDS group proves the importance of individual examinations to explore the expansion of renewables. Nonetheless, the studies establish a set of common characteristics that should be considered in modelling 100% RES, such as follows: the selection of the optimal renewable energy technologies with storage options, accommodating for variable natures of the renewable resources and attaining the cost-optimal energy system. In addition, certain energy system modelling tools were selected in the investigations, such as PLEXUS, EnergyPlan or LEAP, as summarized in Table 3.2, which was also the case for those studies conducted on the Barbados energy system. These modelling tools are further examined in Chapter 5 with a modelling classification scheme to validate the selection of the open-source energy system modelling tools for this investigation.

Chapter 4 – The energy system of Barbados

4.1. The goal of a 100% RES by 2030

The Government of Barbados (GoB) aims to attain a 100% RES by 2030 for social-economic survival. The island has a rich history of successfully adopting renewable energy technologies, as observed in the solar hot water (SHW) industry and has proven renewable energy resource potentials in the form of wind energy. Simultaneously, the island has made several policy targets regarding sustainable development and increasing the renewables' share to achieve a 100% RES by 2030. Based on domestic renewable potentials alone, Barbados has several options to replace fossil fuel generation.

The 100% RE system represents a clear, concise policy target for the current government and will likely stay that way moving into the future. Except for the Barbados National Energy Policy (BNEP) 2019, most previous scenario analyses or modelling of possible futures for the Barbadian energy system were conducted using closed commercial or black box modelling tools. The closed nature of these black-box tools prevented local government agencies from critiquing key results. Using these models does not garner transparency regarding the policy directions, especially considering the intensive role of international donor agencies in funding most of the significant energy initiatives in Barbados in the form of policy-based loans. An open and flexible ESM to conduct future scenario analysis and review current policy report recommendations may serve as advantageous to stimulate a frank dialogue regarding the most sustainable future of the Barbadian energy system.

4.2. Climate, Geography and Population

Barbados is the most easterly of several SIDS in the lesser Antilles Island group of the Caribbean, located at 13°10' N latitude and 59°30' W longitude. The climate is tropical, with a constant temperature that rarely descends below 21 degrees Celsius. The wind resource is steady, constant, and reliable in its direction and is the primary driver of hurricanes that devastated the region (Alleyne 2014). However, the island experiences significantly fewer hurricane events than its neighbours to the northeast (Scruggs and Bassett 2013). Additionally, the excellent wind resource has not been unnoticed, as in colonial times, Barbados had the second-highest number of wind turbines per square mile in the world, second only to the Netherlands (Buchinger et al. 2018)

Most of the 288,367 inhabitants live around the coastal regions (Worldometer 2023). The nation is ranked as the 17th most densely populated globally (World Population Review 2021). The population density was estimated to be 663 inhabitants/km^2, with an urban population share of 44.4% (Healey et al. 2020).

4.3. Energy Sector State of Art

The primary goal of the Barbadian energy sector was to ensure that energy resources were universally available at reasonable prices, which in the past was primarily based on fossil fuel resources (Haynes 2019). Even though the present cost-competitiveness of renewables compared to conventional fossil fuels is well proven, the energy sector remains dependent on fossil fuels for power generation and transportation. As recent as 2023, a summary of the sector's key statistics is shown below in Table 4.1 (Healey et al. 2020; Haynes 2023). However, the information in Table 4.1 needs to be updated on official government sources; however, the composition of the energy sector remains the same, with the transportation and commercial sectors comprising the highest shares of final energy consumption. In addition, as shown in Figure 4.2, diesel fuel retained the highest share of electricity generation in conventional dispatch in 2023.

Table 4.1. Summarising key energy sector statistics (Healey et al. 2020; Haynes 2023)

Category	Data
Installed capacity (2023)	286.6 MW
Renewable energy installed capacity (2023)	(90 MW)
System Peak demand (2015)	(167.5 MW)
Total generation (2023)	996 GWh
Electricity access (2023)	100%
Total installed customers (2023)	130,858

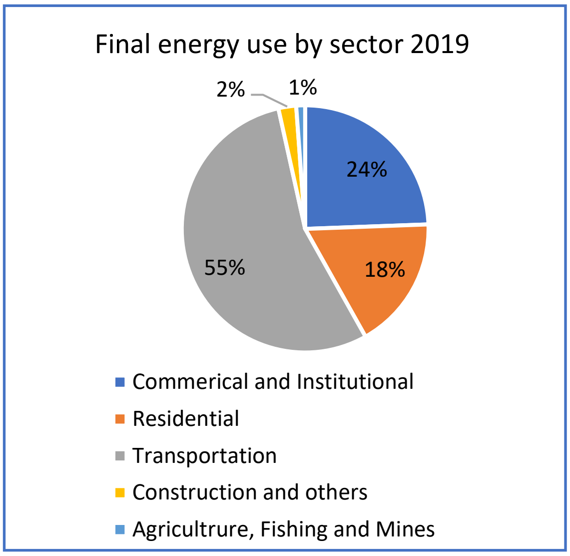

Figure 4.1. Summary of final energy use by sector 2019 (Miller 2020; Haynes 2023)

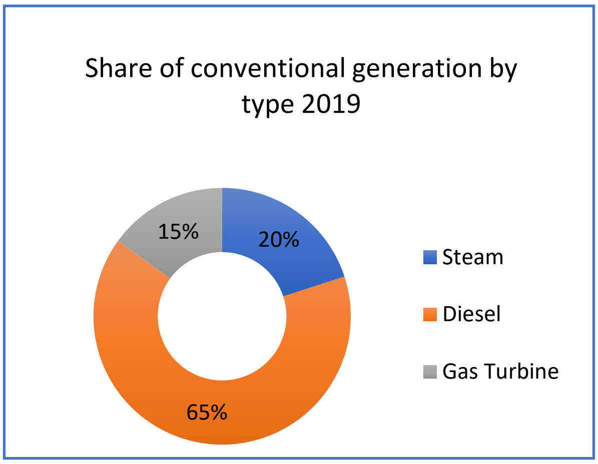

Figure 4.2. Share of generation dispatch 2019 (Miller 2020; Haynes 2023)

4.3.1. Domestic Supply

The island has managed some domestic production of natural resources, and the average total energy supply (TES) between 2006 to 2015 was approximately 11,654 boe/day (Haynes 2015), which has not changed significantly since 2019 (Miller 2020). Local oil wells produce about 820 barrels of oil a day (bopd), slightly less than the 1000 bopd in the previous decade. However, this production accounts for about 10% - 15% of the total annual requirements, which is exported to Trinidad and Tobago for processing for an equivalent amount used for power production by the local electric utility (BNOCL 2021; Division of Energy 2021)

Natural gas is produced at about 2000 million cubic feet per day (MCF/day) (BNOCL 2021). The distribution network services over 22,000 residential and commercial customers (Espinasa et al. 2016). Plans for supplementing these resources from Trinidad and Tobago are currently at the development stage (NPC 2021). The status of domestic natural gas in the long-term is yet to be confirmed by supplemental investigations.

4.3.2. Electricity Generation

Perlack and Hinds (2001) estimated a minimum baseload demand of 80 MW in analyzing a sampled daily demand profile. The demand follows a typical daily weekday demand by increasing during the day due to air conditioning, commercial businesses, and household appliance use, which peaked at 120 MW. Espinasa et al. (2016, 10–11) showed that the peak demand increased between 1993 to 2013, reaching a maximum in 2010 at 165.5 MW. However, since 2015 the peak demand has been declining due to limited economic growth and the expansion of distributed solar electricity. In 2013 the total demand was 912 GWh; however, as recent 2019 and 2020, the demand was 943 GWh and 843 GWh, respectively (IRENA 2016, 117–19; Research Department 2020). The most recent drop in demand can be attributed to the tourism industry, which contracted significantly due to the COVID-19 pandemic.

4.3.3. Costs of Electricity

The utility charges electricity rates using a base rate and the Fuel Clause Adjustment (FCA) indexed to Brent Sea crude oil (Perlack and Hinds 2001). Variations in the electricity rates are due to changes in the fuel charge which fluctuates with the international oil price. Similar to the other fossil fuel-dependent SIDS, the public immediately suffers from the volatility of international oil, reflected in higher energy prices that trickle down to the other economic sectors. In addition, the subsidization of petroleum products cost the GoB over 3 million BBDs a month in 2011 (Haynes 2019). Consequently, the retail energy prices fluctuate significantly, ranking as one of the highest SIDS in the region (Haynes 2019; Henry et al. 2015).

4.3.4. Path to a 100% Renewable Energy System – Regulatory Framework

The first authentic energy policy was the *"Barbados Energy Policy 2007*" according to GOB (2019, 38–39), this document intended to provide general direction for the energy sector that also included the exploitation of renewable energy sources and exploring the potential of offshore petroleum wells. This policy governed the exploration and production of offshore oil to ensure the industry's long-term sustainability, provided that offshore oil resources were shown economically viable in the long term.

Barbados continued to experience much of the challenges as other SIDS in the form of limited expertise in technical areas and challenges in attaining local funding to support sustainable development policy. Consequently, the government entered a formal technical assistance agreement with the Inter-American Development (IADB) to develop a "*Sustainable Energy Framework (SEF) for Barbados*" (IADB 2009b). The policy report recommended a 29% share of renewable electricity consumption in the power sector and a 22% reduction in electricity consumption (GOB, Stantec, and Castalia 2010). Ultimately, the policy did not focus on expanding specific renewable energy technologies and predates the current policy direction of a 100% RES target. More specifically, regarding scenario analysis conducted to examine the targeted 29% mix of renewables in the power supply, the modelling framework or tools, assumptions, methodologies, and approaches were not published in the report. However, the SEF benefited from the early expansion of renewables and funded several supporting programmes that aided GoB in improving future policy planning (Haynes 2015).

4.3.5. Barbados National Energy Policy 2019

The latest energy policy establishes a flexible framework for guiding the adoption of new renewable energy technologies. The policy has several specific energy targets: to attain 100% renewable energy by 2030; to achieve a 100% reduction in fossil fuels by 2030 with transitionary goals of 49% reduction in fossil fuels and a 52% increase in renewable energy by 2023 (GOB 2019). The final proposed energy system was a 76% renewable energy mix. However, the analysis did not concentrate on proving the feasibility of the energy system at an hourly time interval or a detailed technical description of the final energy mix for the final 100% RES.

4.3.6. Renewable Resource Potential

There are no official studies on the on-site potential of the island's wind, solar, and biomass resources. Instead, most of the research regarding viable renewable energy resources was available from expert opinions on the technical potentials of the resources and several consultancy documents prepared for the GoB (GOB 2019; IRENA 2016; BL&P 2014). For example, Rogers (2017, 9)concluded that the technical potential of the wind resource was possibly around 400 MW based on mainly satellite and weather information that was optimized in the WindFarmer Pro software package. Most of the renewable energy potentials were based on the following: the IRENA Roadmap for Barbados (2016), Integrated Resource Plan of the Barbados Light and Power (2014), and the Electricity Market Study by Hohmeyer (2017).

4.3.7. IRENA Roadmap

In 2015, the GoB engaged the International Renewable Energy Agency (IRENA) to develop a Renewable Energy Roadmap supporting renewable energy policy planning (IRENA 2016). The study aimed to examine the transition to higher shares of renewables in the Barbados Energy System using LEAP and PLEXUS energy system models (ESMS). As summarised in Table 4.2 below, the study investigated low oil prices, electric vehicles, and energy efficiency scenarios. The scenarios were modelled between the timeline of 2014 to 2030, with recommended percentage dispatches for each renewable energy and storage technology. The primary energy mix recommended for the Barbadian energy system was a 76% RE mix in the reference scenario summarised in Table 4.3 below. Other scenarios were also examined based on changes in the oil price, the demand for electric passenger vehicles and the degree of energy conservation. However, the study did not examine a 100% renewable energy system for two main reasons.

- The viability of the 100% RES depended on utilizing a biomass potential of 54 MW, which would require 16 million tonnes of sugarcane per year from 20,000 hectares of land (IRENA 2016, 19–20). However, as recent as 2016, only 7,000 hectares of arable land for sugarcane production may be available (Indexmundi 2021). Based on this scenario, a sustainable importation of biomass resources was recommended to increase the resource potential to attain the 100% RES.
- The analysis of storage options was limited to batteries instead of pumped hydro storage. Consequently, the scale of the battery storage required for a 100% RES would substantially increase the system costs, making this scenario infeasible (IRENA 2016, 61–62).

Table 4.2. Scenarios in the IRENA Roadmap (IRENA 2016).

Scenario	Share of renewable energy (%)	Annual costs (Mio. BBD)
Reference scenario	76	236
Energy efficiency Scenario	80	184
Electric vehicle conservation scenario	75	245
Low oil price scenario	68	246

Table 4.3. Installed capacities used in the 76% RES reference scenario (IRENA 2016, 41).

Technologies	Installed capacities (MW)
Low-speed diesel	78
Medium-speed diesel	33
Gas turbine	11
Waste heat plant	2.2
Bioenergy	18
Utility scale solar	110
Distributed scale solar	45
Utility scale wind	155

4.3.8. Electricity Market Study

The electricity study by Prof. Dr. Olav Hohmeyer consisted of several scenarios that examined a 100% RES using pumped hydropower to achieve a dispatch with the lowest levelized cost of energy (Hohmeyer 2017). The main scenarios for the target year of 2035 are listed in Table 4.4 (Hohmeyer 2017, 78). These were examined using a spreadsheet-based model to examine scenarios to attain an energy system with the lowest levelized costs. These renewable resource potentials were summarized based on recent investigations that were not officially released to the public during this investigation.

However, the findings were validated by energy sector stakeholders with reliable expertise on the island through stakeholder interviews.

Table 4.4. Summarizes the main scenarios examined in the Electricity market study for Barbados (Hohmeyer 2017, 78–80).

100% RES Scenario	Wind (MW)	Solar (MW)	King grass (MW)	Bagasse and river tamarind (MW)	Solid waste-to-energy (MW)	Diesel/ Biodiesel (MW)	Storage generation (MW)	Storage pumping (MW)	LCOE (BBD/ kWh)
Wind, solar PV, Waste-to-energy combustion	265	265			11	166.7	196.8	307	0.3883
Wind, solar PV, king grass, waste-to-energy combustion	232	232	26		11	144.8	172.9	253.9	0.4004
Wind, solar PV, king grass, waste-to-energy.	200	200	40		11	131.6	156.8	199.8	0.4331
Wind, solar PV, bagasse, WTE combustion	219	219		25	11	151.9	180.6	248.3	0.4143

4.3.9. IRP Report and the Barbados National Energy Policy

The Integrated Resource Plan (2014) of the BL&P is the most outdated study but remained the most reliable source of cost information and possible dispatch options. The IRP was used in both the IRENA Roadmap (2016) and Electricity market study as written by Hohmeyer (2017). The energy system modelling tool used in the investigation was PLEXUS which examined a high, base, and low case for the demand with various dispatch options to introduce more renewable energy into the energy mix.

As mentioned in Section 4.3.5, the Barbados National Energy Policy 2019 remains the current official policy document of the GoB that states a policy target of a 100% RES (GOB 2019, 77). The policy ensures that future energy policies satisfy specific criteria to achieve maximum sustainability using a multi-criteria approach (MCA) that considers quantifiable economic, environmental, and social impacts. The study examined a 76% share of renewable energy in the power generation sector, as listed in Table 4.5 below. The IRENA Roadmap and the IRP studies are the only studies that utilized commercial energy system modelling tools similar to those used in the studies examined in Table 3.2 (GOB 2019, 48)

Table 4.5. The installed capacities for the 76% RES mix examined in the BNEP (GOB 2019)

Energy source	Potential Installed Capacity (MW)
Solar centralized	205
Solar decentralized	105
Wind onshore	150
Wind offshore	150
Biomass and waste-to-energy	15
Energy storage centralized.	132
Energy storage distributed.	68

Chapter 5 – Creation of criteria used to select modelling tools for the investigation

5.1. Energy system model criteria

A key aspect of all the investigations examined in Chapter 2 is selecting the appropriate energy system model (ESM), as highlighted in Table 3.2. Several models were mentioned, and LEAP and PLEXUS ESMS were utilized in the past to analyze the Barbadian energy system (IRENA 2016, 22,102). These energy system models were compared to the open-source modelling tools to conclusively show that the open-source modelling tools were suitable for this investigation.

An “Energy system model” (ESM) or “energy modelling tool” are different terminologies referring to the same thing, which for this investigation will be thereby referred to as an energy system model (ESM). Hilbert et al. (2018) define ESMS as a tool or combination of tools built employing mathematical approaches called generators comprised of predefined sets of equations or represented technologies to systematically analyze and conceptualize a problem or processes in energy systems. Specific uses of energy ESMS can be summarized as follows: to examine interactions across the energy system or to examine several possible pathways to achieve decarbonization of an energy system (Bhattacharyya and Timilsina 2010b). Prina et al. (2020) further argued that energy system modelling is crucial for defining energy policy targets or pathways and identifying issues regarding selecting the best strategies for the future energy system.

Beeck (1999, 7–8) argued that ESMS are developed to address specific questions and, as such, are only suitable for that intended purpose. Therefore, an ever-increasing array of ESMS continues to be developed according to the needs of researchers. Urban et al. (2007) noted that the need for ESMS by developed nations created a paradigm in developing early energy models, as most were created only for developed industrialized nations and fulfilled all the requirements for strictly analyzing these specific energy systems. Notwithstanding the numerous varieties of ESMS and research conducted using these tools, Bhattacharyya and Timilsina (2010b) showed that most of the earlier ESMS were inadequate for capturing the characteristics of developing countries, including SIDS. Nonetheless, as shown in Chapter 3, more studies have been focused on developing nations, specifically SIDS and other insular island systems, in the last six years. These investigations have addressed most of the inadequacies of early energy system modelling of developing nations using bottom-up simulation or optimization models. Bhattacharyya and Timilsina (2010a, 506–7) supported that most bottom-up, optimization accounting type ESMS with scenario analysis are the most suitable for modelling the inclusion of renewables in the energy systems of developing nations. The research showed that top-down econometric approaches are used to look for optimal solutions in energy system analysis, which is not always possible given the unique constraints of developing nations. Bhattacharyya and Timilsina (2010b) further argued that top-down modelling approaches are inappropriate for dealing with prevalent informal economic activities, reliance on non-marketed fuels, and inefficient technologies, which are distinct features observed in developing countries nations as opposed to developed nations.

At the same time, other authors also support that in examining high shares of renewables, such as a 100% RES that most studies using ESMS must perform the investigations at high temporal and hourly resolutions, which a typical for most bottom-up simulation models (Hansen, Breyer, and Lund 2019, 474–75). Specifically, regarding 100% RES, Connolly et al. (2010, 19–20) also supported this, showing that in examining 16 energy system models, only seven tools could model a 100% RES as follows: EnergyPlan, H_2RES, Invert, Mesap PlaNet, INFORSE, LEAP, SimREN. Specifically, EnergyPLAN, Mesap PlaNet, H_2RES and SimREN, which used time steps of 1 hour or less, were best for optimizing the energy system to accommodate the fluctuation in VRES. The research further argued that modelling at an hourly resolution permits the modelling of energy system flexibility in detail to understand sector-coupling and demand response, accommodate for storage and the power grid requirements, and include dispatchable renewables regardless of location or time in the hourly cycle. Finally, Heard et al. (2017) corroborated that in the case of developing nations, analysis at the hourly resolution is the only way to test the technical and economically feasibility of a 100% RES using a bottom-up or even hybrid energy analysis instead of solely top-down analysis.

5.2. Open-source science

Chang et al. (2021) argued that energy system modelling is critical to public debate and support for political decisions or policies by quantifying the impacts of changes in the energy system. Morrison (2018) argued that a critical requirement for garnering the support for an energy policy is public transparency, which requires that the models used in the investigation should be fully documented and that the datasets be made open for inspection by the public. The author further argued for model developers to publish equations used in the examination for third party review. In retrospect, all of the ESMS examined in Chapter 3, were closed or "black box" models implying that the models were developed using proprietary software developed by various institutions (Lopion et al. 2018; Connolly et al. 2010). However, utilization and modification of the software for research are limited to these institutions. Therefore, quality control is reserved only for the original model developers. Hilpert et al. (2018) and Harewood et al. (2021), noted that the challenge in using these black-box models is the inability to review the model structures by third parties. Bohm (2019) discussed that for most commercial black-box ESMS, parameters such as economic conditions and other technical constraints are fixed depending on the purpose of the model.

The transition towards greater openness in energy system modelling has gained popularity within the past decade, with over 40% of the models used in literature being open-source (Lopion et al. 2018, 160–61). For this reason, several authors in the literature support the creation of the Openmod initiative to promote the use of open energy system models by providing a catalogue of open-source code and a network of institutions to foster greater transparency in energy system modelling (Simon Hilpert et al. 2017; Andre Harewood, Hilpert, and Dettner 2021). In using open-source ESMS, the code is open, and the raw results are available for analysis (Lopion et al. 2018). More importantly, as the model code is open access, the models are free for use in an investigation without licensing fees (Ringkjøb, Haugan, and Solbrekke 2018).

Oemof is an open-source tool kit generator that may be used to create a new energy system model for research or expand a previously developed model for energy system analysis (S Hilpert et al. 2018; Bohm 2019). Hilpert et al. (2020) created the oemof-jordan model to examine cost-optimal renewable energy expansions for the future Jordanian energy system with success. Also, Maruf (2021) used renpassG!S, another model created from the oemof toolkit made to investigate the role of sector coupling in attaining a 100% RES for the North Sea Region. Most recently, Harewood et al. (2021) recently utilized the oemof-barbados ESM for scenario analysis, demonstrating that 80% cost-optimal renewable energy systems were possible. Levelized energy costs ranged for the cost-optimal scenarios from 0.17 to 0.36 BBD/kWh with moderate cost increases for 100% renewable energy system configurations. Additionally, the investigation showed that pump storage is a good option for the Barbados energy system. In evaluating the use of energy system models in investigations, Chang et al (2021) showed that these tools could be grouped as either indirect or direct policy support. In the case of indirect policy support, the models used in investigations contributed to discussions on energy policy or validated official policies. Whereas, in the case of direct policy support, the models were used in investigations by an official government-based organization to inform policy decisions. The authors showed that the use of open-source ESMS is more prevalent and established for indirect policy support such as scientific investigations.

5.3. Classification scheme used to select the model

A set of criteria was selected based on the studies conducted in Chapter 3 and several sources of literature as follows: Lopion et al. (2018), Connolly et al. (2010), Prina et al. (2020), Ringkjøb (2018), Müller et al. (2018) and Hall and Buckley (2016). These specific criteria were summarized as follows:

- The selected ESM must model a 100% RES, inclusive of power generation and capable of sector-coupling, as highlighted in Harewood et al. (2021, 120), showing that sectors of critical importance in the Barbadian energy system are vehicular transport and cruise transport sectors.

Furthermore, in continuing this work, there is a need for a power grid model to examine grid expansion to accommodate higher shares of renewables on the grid.

- The ESM must utilize bottom-up analysis as the primary form of analysis to investigate high shares of renewables in an insular energy system.
- The ESM must provide a least-cost optimized dispatch based on the merit order to ensure that the most economically feasible dispatch, which meets the demand at every hourly interval, is found.
- The simulation of multiple demand profiles from the residential, commercial, industrial, transportation or other sectors must also be incorporated.
- The ESM should also be highly flexible in capabilities such as modelling all current and future renewable power generators and storage technologies in addition to conventional gensets.
- All results must be available as CSV files for external examination by utilities, funding agencies, academic institutions, and the GoB.

Based on these criteria, a classification scheme was created and used to evaluate the suitability of a model as follows: purpose - general or specific; modelling approaches; methodology; geographical coverage; sectoral coverage and time horizon. The essential details regarding the classification can be summarized in Table 5.1 below. The criteria and classification schemes were used to analyze several closed black box models used in literature to open-source modelling tools. The best model/models based on the research goals of this investigation were selected using the classification scheme.

Table 5.1. Summarises the classification scheme to analyze ESMS for the study (Lopion et al. 2018; Prina et al. 2020; Ringkjøb, Haugan, and Solbrekke 2018; Müller, Gardumi, and Hülk 2018; Hall and Buckley 2016)

Model characteristic	Structure	Specific relevant for Barbados
Simulation of a 100% RES	Examinations of high shares of renewables specifically, a 100% RES	• The model must be capable of modelling a 100% RES.
Purpose	General – forecasting or predictive, exploring or scenario and backcasting Specific – Power system analysis, scenario, investment decision support, operations decision	• Forecasting models are omitted as these are used in top-down models and proven inappropriate for this investigation. • As the investigation is an examination of a 100% RES scenario and backcasting model was considered. • Power system analysis models were also evaluated due to the research goals.
Modelling approach	Top-down, bottom-up or hybrid modelling	• Primary bottom-up modelling approaches have been used in literature for examining 100% RE systems in SIDS or insular island systems; therefore, models with a bottom-up

Model characteristic	Structure	Specific relevant for Barbados
		approach were considered for this investigation Table 3.1 and Table 3.2.
Methodology	Simulation, optimization, equilibrium, accounting, multi-criteria, stochastic/Monte-Carlo	• As ESMS with a bottom-up modelling approach were selected for the examination, mainly optimization models were evaluated for this investigation, except EnergyPLAN.
Mathematical approach	Linear programming, mixed integer programming, dynamic programming	• Linear programming or mixed inter programming models were evaluated as the model must optimize the energy mix to attain the cost-optimal dispatch.
Geographical coverage	National, regional, global/community or a single project	• The investigation is 100% RES; therefore, models with a national coverage were evaluated.
Sectoral coverage and time horizon.	Energy sectors, other specific sectors, or the overall economy	• The model must examine several energy-consuming sectors, such as power demands from e-mobility and cruise ship tourism.
Spatial and temporal resolution	short, medium, or long-term	• In the case grid model, a high spatial resolution is required to examine the line loadings at buses in the power transmission and distribution grid. • Models that can examine the energy system at a 1–3-hour time step were evaluated for the investigation.
Degree of openness	Accessibility of model code and results for external examination.	The model should be open for external examination, such as utilities, public institutions, and academics.

5.4. Purpose

5.4.1. General-purpose

All ESMS were developed to answer a given research question. Both studies Hall and Buckley (2016, 612–13) as well as Beeck (1999, 7–8) support that ESMS can be categorized for either general or specific purposes. The general purpose of an ESM can be defined as one of the following: forecasting or predictive, exploring or scenario and backcasting. Models created for forecasting are used with top-down models to make predictions of the future energy system based on analyzing trends from present and past data (Beeck 1999). Ringkjøb et al. (2018, 444–45) showed that exploring or scenario ESMS mainly investigate future long-term scenarios to evaluate various policy' impacts. By exploring future scenarios, a limited number of intervention scenarios are compared to a "business-as-usual" scenario

(Beeck 1999, 8–9). Models created for forecasting were disregarded, as these are typically used in top-down models, which are not suited for investigating a 100% RES.

5.4.2. Specific Purpose

In categorizing models by a specific purpose, there are several opinions in literature, as seen in Ringkjøb et al. (2018), Hall et al. (2016), and Jebaraj et al. (2006). According to Hall et al. (2016, 612–13), the specific purpose of an ESMS is descriptive and considers the particular focus of the model, which serves to differentiate between the model objectives. Ringkjøb et al. (2018, 443–44) defined models by specific purpose to derive four main models: power system analysis tools (PSAT), operation decision support tools, investment decision support tools and scenario tools. As a research goal is the examination of the 100% RES for Barbados an investment model was selected as the best initial approach to understand - how the 100% RES could be built. Therefore, investment decision support tools were considered for use in this investigation. Based on the research question to examine grid reinforcement to accommodate the 100% RES, ESMS for power system analysis otherwise referred to as (PSAT) were considered for this investigation. In addition, as the study intends to investigate possible futures or scenarios for a 100% RES, scenario tools were examined for this investigation as described in Table 5.2 below.

5.5. Modelling Approaches: Top-down, Bottom-up and Hybrid

ESMS can be classified by analytical approach as top-down, bottom-up or hybrid. Ringkjøb et al. (2018, 445–46) stated that a bottom-up or engineering approach is based on detailed technical descriptions of the energy system instead of a top-down modelling approach or economic approach that considers macroeconomic relationships and long-term changes. Therefore, the bottom-up modelling approach focuses on a high degree of technical detail to assess future energy demand and supply. As top-down modelling approaches were shown unsuitable for this investigation, as explained above, only bottom-up modelling approaches were considered.

5.6. Methodology

Several methodologies are described in the literature, with some repetition between various sources. Bhattacharyya and Timilsina (2009) define a methodology in energy system modelling as a set of methods or systematic approaches for accomplishing a task by following a philosophy to analyze the energy problem. According to researchers (Herbst et al. 2012, 126–27; Ringkjøb, Haugan, and Solbrekke 2018, 444–45), methodologies can be economic-equilibrium, optimization, or simulation. Beek (1999, 13–14) further specified models by modelling approach and methodology, noting that top-down econometric models use either optimization or simulation approaches. In contrast, the bottom-up models in the literature are known for mainly using an optimization approach.

Similarly, most ESMS described in Table 3.2 used a bottom-up approach and optimization methodologies, except for EnergyPlan, which Prina et al. (2020) classified as a bottom-up simulation model. Also, economic-equilibrium methodologies were not evaluated as they were not used extensively to examine 100% RE systems in the literature. In addition, as Helgesen (2018) noted, in some cases, optimization models were categorized as partial equilibrium models as these balance the demand and supply in the sectors covered.

5.6.1. Optimization

ESMS optimize energy investment decisions endogenously by mathematically optimizing a preferred set of technologies given constraints using either to achieve a specified target leaving the prices and quantities fixed at an equilibrium (Beeck 1999, 14–15). Additionally, Prina et al. (2020, 5–6) and Ringkjøb et al. (2018, 444–45) both noted that most optimization models utilized linear programming (LP) mathematical approach, which optimizes, minimizes, or maximizes the system as an objective function, subject to balancing the supply and demand on the power grid as a constraint. In the case of linear programming dispatch optimization, the dispatch is optimized following a merit order logic.

Prina et al. (2020, 5–6) also specified optimization models as either perfect-foresight or myopic approaches. Perfect foresight assumes complete information about the energy system model past and future requirements to analyze the energy system to find a cost-minimal expansion pathway (Kotzur et al. 2021). Therefore, all the information, boundary conditions and information are part of the optimization (Lopion et al. 2018) In a myopic approach, the energy system is optimized or simulated for individual time frames based on the results of the former time frame (Lopion et al. 2018). Therefore, in optimizing the energy system, the model is reduced to a limited number of years shorter than the full timeframe and decisions are re-iterated during the modelling period (Fuso Nerini, Keppo, and Strachan 2017).

As bottom-up modelling tools were the best for this type of investigation of a 100% RES, most models examined Table 5.1. utilized a linear programming mathematical approach. Several literature sources have validated the assumptions and information used in this investigation which includes the following: Electricity Study, IRP Report, IRENA Roadmap and Barbados National Energy Policy 2019. Consequently, complete knowledge of crucial information such as the following is available: cost trends, consumption, the decay of performance of specific technologies or decommissioning dates can be assumed. Based on these proven sources, the main aim is to model a final 100% RES for Barbados; therefore, a perfect-foresight optimization model was deemed appropriate for this investigation.

5.7. Geographical and sectoral coverage

Beeck (1999, 15–16) states that geographical coverage defines the level at which the analysis occurs. Depending on the ESM, it can vary from a regional level inclusive of multiple nations or a local level of regions within a nation. National ESMS consider world market conditions as exogenous variables but examine all significant sectors within the country (Hiremath, Shikha, and Ravindranath 2007). The geographical coverage was focused on a national level as the investigation is a 100% RES. Prina et al. (2020, 4–5) defined geographical coverage as either single or multi-node approaches. Models that focus within a nation at a local level using bottom-up approaches on disaggregated data. This research further states that a single node simplifies some interactions in the energy system. For example, the system is measured as an ideal perfect transmission system without bottlenecks or constraints in electricity generated by the transmission and distribution limits in the power system. The system can be considered an ideal perfect transmission system to model the 100% RES for Barbados. However, for examining the power grid, both the transmission and distribution limits of the power system must be considered.

Sectoral coverage differentiates between whole energy system models or single sector models (Hall and Buckley 2016, 613–14). Harewood et al. (2021, 120–21) showed that sectoral coverage, particularly transportation is essential when modelling the 100% RES for Barbados; therefore, whole energy system models were considered for this investigation.

5.8. Spatial and temporal resolution

The spatial resolution and GIS-based approaches are essential in modelling an energy system with high penetrations of intermittent renewable energy sources, or VRES, in the form of wind and solar power (Martínez-Gordón et al. 2021). The authors further argued that poor spatial analysis leads to underestimating geographical variability and overestimating the uncertainty and flexibility requirements to balance supply and demand. The potential of variable renewable energy systems, their generation costs, and generation profiles depends on their spatial location and availability, as for wind and solar radiation (Prina et al. 2020, 10–11). The spatial distribution of the resources usually smothers variability associated with renewable electricity generation. Also, the spatial resolution is usually improved with an increase in the number of nodes. A low spatial resolution is a trait of single-node ESMS. In contrast, using several nodes characterizes a high spatial resolution, as is common in power system analysis tools used to examine power grids. Harewood et al. (2021) used a limited number of nodes in the oemof-barbados to examine the effect of ship-to-shore charging on the 100% renewable energy system of Barbados. However, for accurately examining the power grid specifically for instability, the energy system would be divided into several nodes represented by primary transformers in the transmission and distribution grid.

The temporal resolution or time step impacts the evaluation of the system behaviour within one specific year (Lopion et al. 2018, 157–58). The higher the temporal resolution, the more accurately fluctuations of renewable energy resources are examined in the model, which may vary from a few milliseconds in the case of power system analysis tools to model to an hourly resolution (Ringkjøb, Haugan, and Solbrekke 2018, 452–53). Consequently, temporal resolution is essential when modelling energy systems with large shares of VRES. For example, energy models with a low temporal resolution overestimated the variable renewable energy penetration and underestimated the investment in renewables.

5.9. Openness and transparency

Ihlemann et al. (2021) noted that most energy system models were built for a particular energy system and are hardcoded with model features that may need to be changed as more modelling challenges become apparent. For the investigation, flexibility was an important consideration such that the ESM selected should be capable of modelling several components as follows: conventional gen-sets; renewable resources including biomass, solar wind generation; storage technologies such as pump hydropower, lithium-ion batteries; and several flexible generation technologies as relevant for the Barbados energy system (Hohmeyer 2017, 10–11; IRENA 2016, 41–42). Furthermore, as noted in the Barbados Energy Policy (2019, 57–58), the policy was flexible. New technologies for storage and generation may be incorporated into the energy mix based on economic, environmental, and social criteria. Consequently, ESMS were evaluated for this investigation based on their capacity to model several renewable sources of generation, storage technologies or conventional gensets, as shown in Table 5.2. In addition, the ESMS were evaluated for openness based on the licensing, which was either commercial or open source. Only the open-source energy ESMS are open and have both the results and model code available for third party analysis (Simon Hilpert et al. 2017; S Hilpert et al. 2018; Wingenbach, Hilpert, and Günther 2017).

5.10. Evaluation of energy system models

The criteria in Table 5.1 were used to analyse the ESMS selected for the investigation as shown in Table 5.2. Based on literature and previously conducted scenarios analysis on Barbados and the studies examined in other SIDS as discussed in Table 3.2 the following ESMS were evaluated: LEAP, EnergyPlan, PLEXOS, OSeMOSYS Mesap PlaNet, PyPSA and Oemof. A summary of these ESMS was completed in Table 5.2 below. The models were shown to have similar capabilities, all except for EnergyPlan, which was a simulation model and, based on the literature, was limited to specific electricity storage and electrolysis. All the models except for EnergyPlan are capable of using optimization methodologies. However, the critical distinction is that none of the models, except Oemof and PyPSA, are open access to the code and are without licensing fees in addition, the results are available in a CSV format that can be analyzed externally. Consequently, oemof was selected for techno-economic modelling of the energy system described in Harewood et al. (2021), and PyPSA was selected as the ESM to model the 100% RES on the Barbadian power grid.

Table 5.2. Summaries the matrix used to analyses various black-box energy system models to the open-source energy system models (Prina et al. 2020; Hall and Buckley 2016).

Model	Purpose	Renewable's inclusion	Conventional inclusion	Storage inclusion	Grid	Simulation of a 100% RES and electricity	Modelling Approach	Methodology	Mathematical approach	Geographical coverage	Sectoral coverage	Temporal resolution & time horizon	Programming language / licensing
EnergyPlan (Prina et al. 2020, 6–7) (Hall and Buckley 2016, 615–18)	General: Scenario, investment decision support Specific: energy supply and demand with a focus on future options.	Wind (Onshore & Offshore), solar PV, wave power, river hydro	All	Electricity storage unit (hydro or battery), electrolysis, battery electric	Import/export	Yes	Bottom-up	Simulation	Heuristic	Local, national, regional, continental	Electricity, heat, transport	1-hour Time horizon: 1 year	Visual basic for applications / Delphi pascal Licensing: semi- open source /access
LEAP (Connolly et al. 2010)	General: Exploring or forecasting Specific: demand, supply, environmental impacts, life-cycle analysis-	All	All	All	None	Yes	Hybrid	Accounting, simulation & optimization (Ringkjøb, Haugan, and Solbrekke 2018)	*Linear programming*	Local, national, regional & global	All sectors - transportation, residential, industrial and agriculture	Yearly (Lopion et al. 2018) Time horizon: no limit (Connolly et al. 2010, 6–7)	Other-undefined Licensing: Commercial

Model	Purpose	Renewable's inclusion	Conventional inclusion	Storage inclusion	Grid	Simulation of a 100% RES and electricity	Modelling Approach	Methodology	Mathematical approach	Geographical coverage	Sectoral coverage	Temporal resolution & time horizon	Programming language / licensing
	applicable for developing nations (Hall and Buckley 2016)												
PyPSA (Brown, Hörsch, and Schlachtberger 2017a; 2017b)	General: Investment decision support, operation decision support Specific: PSAT	All	All	All (Generic)	Non-linear/Linear Power Flow, Net transfer capacities (NTC)	Can examine the power grid of a 100% RES.	Bottom-up	Optimization and simulation	Linear programming	Local, national, regional, continental	Aggregated	Hourly –	Python Licensing: open source/ access
Oemof (S Hilpert et al. 2018; Wingenbach, Hilpert,	General: Scenario, investment decision making,	All	All	All	Import/Export, Net transfer capacities	Yes	Bottom-up, top-down & hybrid	Simulation, optimization,	Linear programming,	Local, national, regional, continental	Building, transport, industrial	Seconds to years –	Python licensing Open source

Model	Purpose	Renewable's inclusion	Conventional inclusion	Storage inclusion	Grid	Simulation of a 100% RES and electricity	Modelling Approach	Methodology	Mathematical approach	Geographical coverage	Sectoral coverage	Temporal resolution & time horizon	Programming language / licensing
and Günther 2017)	operation decision support				(NTC)								/access
PLEXOS	General: Investment decision support, operation decision support Specific: PSAT	All	All	All (Generic)	Import/Export, NTC, DC Load Flow, AC Load Flow, SCOPF and FBMC.	_	Bottom-up	Optimization (Mixed-Integer, Linear and Non-Linear)/ Partial Equilibrium	Linear programming	Single project Local, national, regional, continental	All	One minute but usually an hrs. _	Other-undefined Licensing: Commercial
OSeMOSYS	General: exploring, investment decision making	All	All	All	None	_	Bottom-up	Optimization	Linear programming	Local, national, regional, continental	Energy sector	User-defined Time horizon: user defined 10-100 yrs.	GNU MathProg Licensing: Open source/access

Model	Purpose	Renewable's inclusion	Conventional inclusion	Storage inclusion	Grid	Simulation of a 100% RES and electricity	Modelling Approach	Methodology	Mathematical approach	Geographical coverage	Sectoral coverage	Temporal resolution & time horizon	Programming language / licensing
Mesap PlaNet (H. Gils, Simon, and Soria 2017)	General: scenario investment decision making	All	All	All	Import/Export,	Yes	Bottom-up	Simulation and optimization (Bhattacharyya and Timilsina 2010a, 504–5)	Undefined	National, state, regional, global	Electricity, heat, transport	User defined. Time horizon: Unlimited	Undefined Licensing: commercial

Chapter 6 – Oemof Framework

6.1. Oemof concept

In nature and science, multiple phenomena vary in complexity, which may be explained using scientific and mathematical approaches. Therefore, for research, relationships between energy system components such as energy generators, storage technologies, energy consumers and energy carriers are described for analysis using graph theory or network analysis (Wingenbach, Hilpert, and Günther 2017). A network is a set of objects shown as nodes, otherwise referred to as vertices, that have relationships between each other, which are called edges, otherwise referred to as links. Similarly, in mathematics, networks are referred to as graphs and the field of study is graph theory. A directed graph or digraph occurs when a set of objects, otherwise referred to as nodes, are connected such that the edges are directed from one node to another by using arrows with directions. In such a case, the relationship between these nodes is asymmetric (cf. Figure 6.1) (Nagel 2018).

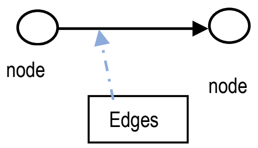

Figure 6.1. Directed graph showing an asymmetric relationship (Own Creation n.d)

A bipartite graph or biograph consists of two separate groups of nodes - group 1 and group 2 such that there exist only edges between these two groups (c.f. Figure 6.2).

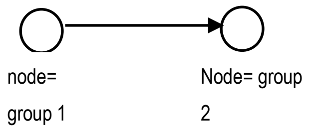

Figure 6.2. Summarizes a bipartite graph used to describe the relationship between two groups (Own Creation n.d).

As this basic terminology has been defined, graph and network theory can be applied to the oemof modelling framework. Within energy system modelling, the entire energy system is represented as graph structures or networks comprised of nodes with connections between them, shown as edges (S Hilpert et al. 2018). The energy system is modelled as a bipartite directed graph, the edges of which represent the flow of energy, carbon dioxide or other goods between nodes. Within the context of this energy system, edges can only exist between nodes of different types (Wingenbach, Hilpert, and Günther 2017, 45). Thus, preventing more than one edge of the same direction from existing between two nodes and avoiding the occurrence of parallel edges by inserting dedicated nodes as buses.

In the model, mathematically, a node represents a balanced space in which the sum of inflows and outflows are equal (S Hilpert et al. 2018, 128). Nodes can be further characterized as entities either on the supply or demand side of the energy system. Conversely, energy sources in the form of fuel or electricity can be understood as a flow that can be transformed from one node to another, as shown in Figure 6.2. Based on the flow of energy, four main types of energy system components can be defined by model users as nodes that represent physical objects; these are as follows: busses, sources, sinks or linear transformations (cf. Table 6.1). Any system component can be interlinked with others to represent the energy system. These components can be specific for several regions interlinked with others via transmission lines. Several energy system components can be represented as nodes, with the flow of energy between these nodes represented as directed graphs. In the case of Figure 6.3. below, the energy system components are nodes connecting to a hub node defined as an electrical grid. Renewable energy generators and flexible conventional generators are represented as sources, also defined as energy flows to the electrical grid. Alternatively, the demand and excess are defined as sinks or consuming entities. The components were summarized as the following symbols below:

- (w) is an energy system component representing a source such as a variable renewable energy power producer, which produces the electrical energy that flows towards the hub/bus.
- (g) is an energy system component that represents a source that is a flexible generator that produces energy that flows towards the hub or bus that acts as the accumulation of energy system components or as connections between producers and consumers of energy or other resources.

Figure 6.4 summarizes the system components used in the oemof-Barbados model, and Table 6.1 below serve to define energy system components in detail.

Table 6.1. Details the major components used in the oemof-Barbados model (S Hilpert et al. 2018; Wingenbach, Hilpert, and Günther 2017)

Components	**Detail**
A bus	A bus, otherwise referred to as a hub, can be understood as a balancing zone. That can have (*n)* number of inflows and (*n)* number of outflows (S Hilpert et al. 2018). The balance of all the flows to a bus is always zero (e.g., The power grid in a region can have several inflows from power plants and several power consumers, thereby ensuring that all the flows into and out of the bus are balanced.)
A source	A producing entity is defined by the flow of direction from a source node such as a power plant to a targeted node such as an electrical grid (S Hilpert et al. 2018). Sources have

Components	Detail
	outflows but no inflows (e.g., The power production of a wind turbine (= outflow from the node), which intern depends on the installed capacity, and the normalized production curve of the turbine (= inflow into the node), which depends on the local wind speed weather data. The electricity production will be fed into the electrical grid in the region where the wind turbine is located.
A sink	A sink is a consuming entity defined by a flow with direction from a source node, such as the electrical grid, to a target node, representing the actual load curve (Bohm, 2019). A sink has inflows but no outflows and is similar to a “source” except that the sign is opposite. Examples of sinks are as follows: 1. The load curve in a region represents the outflow from the node and needs to be pre-defined). It needs to be covered by electricity (= inflow) from the grid in that region. 2. The energy consumers of the household.
A linear transformation	This is an entity that converts energy. This is one inflow and one outflow. The conversion also implies there is also some efficiency factor. (e.g., A power plant converts fuels (= inflow from a fuel bus) to electricity (= outflow to another electrical bus)) (e.g., A transmission line converts electricity (= inflow from an electrical bus) of one region to electricity (= outflow to another electrical bus) of a second bus)) of a second region.

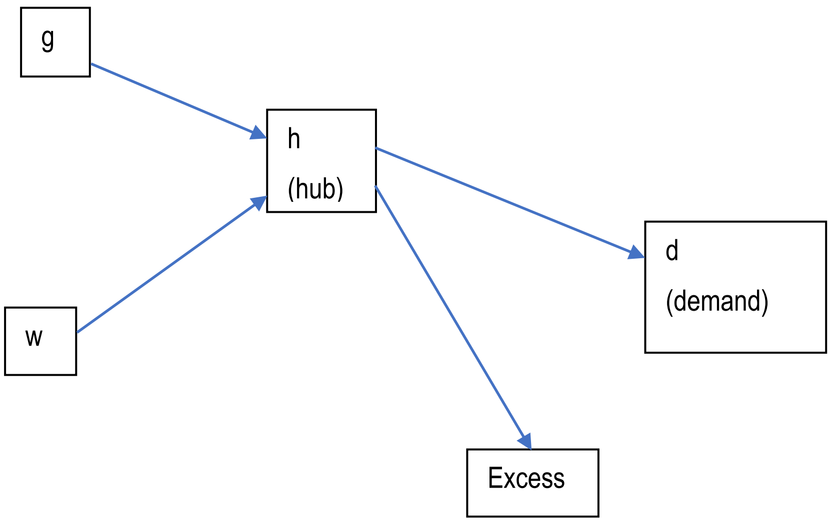

Figure 6.3. Summarizes the energy systems connected as to the hub node (Wingenbach, Hilpert, and Günther 2017)

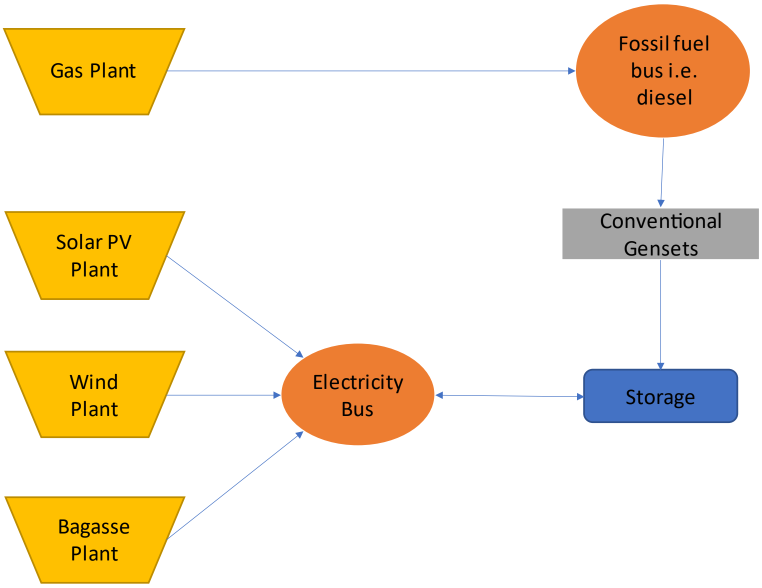

Figure 6.4. Demonstrates a sample energy system and the functions of each energy system as used in the Barbados model (One Creation n.d).

6.2. Oemof packages

Oemof is written in python programming language and uses several python packages for scientific applications such as mathematical optimization, network analysis, graph theory, data analysis, and PostgreSQL/PostGIS databases. Several oemof core modules and libraries are represented as classes used for building the energy system, and these are as follows: oemof.solph package, oemof.network module and oemof.groupings module, oemof.outputlib and oemof-Visio, feedinlib, windpowerlib, demandlib (cf. Figure 6.5). These libraries and linkages are grouped on four levels based on mutual compatibility between the various oemof libraries highlighted in the shaded regions in Figure 6.5 below (Wingenbach, Hilpert, and Günther 2017, 46).

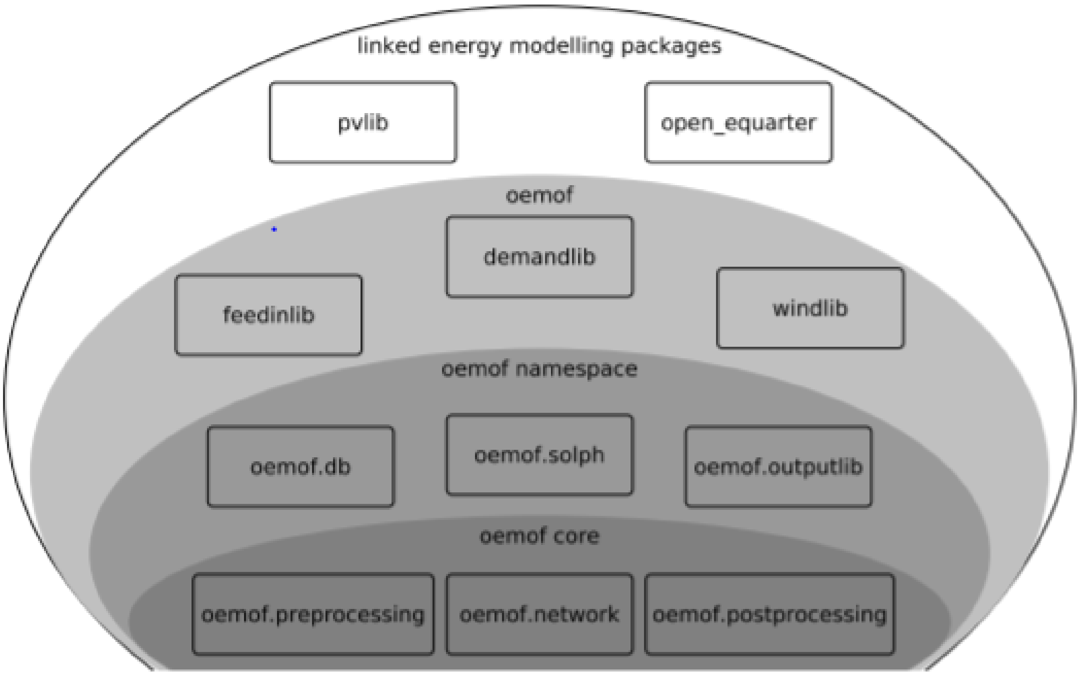

Figure 6.5. Summarizes the major oemof packages, core modules and libraries (Wingenbach, Hilpert, and Günther 2017).

The oemof core layer are graph structures defined as application programming interfaces (APIs), which provide a written description of the energy system and the input and output data for the core-objects (Wingenbach, Hilpert, and Günther 2017, 10–11). The application programming interface (API) is an interface through which python script and other programmes can be used and accessed by model users. The oemof-solph package in the oemof namespace layer creates and solves the linear and mixed-integer linear optimization problem. This module can switch between a dispatch and investment model as the researcher requires using known solvers such as coin-or, glpk, gurobi, cplex or others (oemof 2021). The oemof layer contains independent optimization libraries not based on the graph structures (Nagel 2018; Wingenbach, Hilpert, and Günther 2017). Finally, the outermost layer contains external packages from completed energy system analysis projects used oemof open-source programmes (Nagel 2018, 50–51).

6.3. Optimization and the objective function

With the energy system defined as bipartite graphs and linked to the various libraries in oemof, the model is built as an objective function, which describes the criterion to be minimized or maximized, which can either be a dispatch or investment model. In the case of an investment model, the optimization solves the least-cost investment costs (Maruf 2021; Simon Hilpert, Dettner, and Al-Salaymeh 2020). The optimization was done within the transmission capacity constraints between regions and/or any other technical or economic constraints that the researcher may define. However, for the oemof-barbados model, there was no need to consider the transmission capacity between regions as the island had no interconnected regions for sharing electricity.

The model uses a solver that iteratively approximates the best solution. In the case of the oemof-barbados, several solvers may be used, such as gulk, "COIN Branch and Cut" (CBC) solver, and gourbi, with the latter two being the primary solvers used in this investigation. For example, in using the CBC solver, the least cost result is approached using a mixed-integer linear programming-based branch-and-bound algorithm (Forrest 2020). The algorithm starts using one potential set of allowed variable parameters, such as the operations modes of a set of dispatchable units. However, the variable is altered iteratively by using the least cost setting for the next iteration until the solver approximates the least-cost system gradually for the entire system.

The oemof-barbados model minimizes the total operational costs for the entire time horizon (T) and annualized investment costs of units $u \in U$ and storage investment costs of all storage $s \in S$ in the Barbadian electricity system (Andre Harewood, Hilpert, and Dettner 2021).

The respective objective function comprises endogenous (input) optimization variables, which depend on other variables in the model shown in bold to differentiate between these and exogenous model variables as summarized in *Equation 6.1*. Specifically, the current technology capacities in the optimization model are endogenously determined.

Equation 6.1 $$min: \overbrace{\sum_{t \in T} \sum_{u \in U} c_u^{opex} \boldsymbol{P_{u,t}}}^{operational\ costs} + \overbrace{\sum_{u \in U} c_u^{capex,p}\ \boldsymbol{P_u^{nom}}}^{power\ inv.cost} + \overbrace{\sum_{s \in S} c_s^{capex,e} \boldsymbol{e_s^{nom}}}^{energy\ inv.\ cost}$$

All buses or busbars must be balanced in every step of the problem such that the total of all the incoming flows of the processes must be the sum of all the outgoing flows to the corresponding successors. The exogenous variables were as follows:

- The operational costs c_u^{opex} are variables calculated based on the efficiency η_u of a unit u and its fuel costs c_u^{fuel} according to *Equation 6.2*.
- The annualized investment costs $c_u^{capex}$are calculated based on the lifetime η, weighted cost of capital (wacc) and the specific investment costs of a technology $CAPEX_u$ as well as the fixed operation and maintenance costs (FOM) (c.f. *Equation 6.3*).

Equation 6.2 $$c_u^{opex} = \frac{c_u^{fuel} + c_u^{var}}{\eta_u}$$

Equation 6.3 $$c_u^{capex} = CAPEX_u \cdot \frac{wacc \cdot (1+wacc)^n)}{((1+wacc)^n - 1)} \cdot (1 + FOM)$$

The endogenous variables were as followed:

- The total demand in every time step is composed of different parts with specific load patterns and is assumed to be inelastic. The demand must equal the sum of the supply of all producing units, as described mathematically in *Equation 6.4*. Note that in the case of the storage units, P can also be negative values when the storage is charging.

Equation 6.4 $$\sum_{u \in U} \boldsymbol{P_{u,t}} \cdot \boldsymbol{\tau} = \sum_{l \in L} d_{l,t} + P_t^{excess} \cdot \tau \qquad \forall t \in T$$

For all investment units, the supply is limited by the installed nominal power P_i^{nom} described in *Equation 6.5*, bounded by lower and upper investment limits as shown in *Equation 6.6*.

Equation 6.5 $$0 \leq P_{u,t} \leq P_u^{nom} \qquad \forall u \in U, t \in T$$

Equation 6.6 $$\underline{p_i} \leq P_u^{nom} \leq \overline{p_\iota} \qquad \forall u \in U$$

The energy storage balance in *Equation 6.7* is applied for all modelled storage types. The balance includes standing losses η^{loss} as well as charge and discharge efficiencies $\eta^{in/out}$.

Equation 6.7 $$e_{s,t} = e_{s,t-1} \cdot \eta_s^{loss} - \frac{P_{s,t}^{out}}{\eta_s^{out}} + P_{s,t}^{in} \cdot \eta_s^{in} \cdot \tau \qquad \forall \epsilon S, t \in T$$

Additionally, the storage power is limited by the optimized nominal power shown in *Equation 6.8*.

Equation 6.8 $$-P_s^{nom} \leq P_{s,t} \leq P_s^{nom} \qquad \forall \epsilon S, t \in T$$

For all the RE technologies such as solar PV and wind, the power output is determined by *Equation 6.9*, where $c_{v,t}^{profile}$ is the time-dependent normalized generation profile of the unit $\upsilon \in V$.

The profile data was obtained from renewables.ninja (Pfenninger and Staffell 2016).

- $\boldsymbol{P_{v,t}}$ is the decision variable for a generator, and the constraints are secondary conditions that can be differentiated.
- $\boldsymbol{P_\upsilon}^{nom}$ is the nominal power for a generator.

Equation 6.9 $$\boldsymbol{P_{v,t}} = c_{v,t}^{profile} \boldsymbol{P_\upsilon}^{nom} \qquad \forall \nu \in V, t \in T$$

- Analogous to *Equation 6.5* and *Equation 6.6*, the energy storage content and its maximum investment are bounded, as shown in *Equation 6.11* and *Equation 6.10* below.

Equation 6.10 $$\boldsymbol{e_s^{min}} \cdot \boldsymbol{e_s^{nom}} \leq e_{s,t} \leq \boldsymbol{e_s^{nom}} \qquad \forall s \in S, t \in T$$

Equation 6.11 $$\boldsymbol{0} \leq \boldsymbol{e_s^{nom}} \leq \boldsymbol{\bar{e}_s} \qquad \forall s \in S$$

The dispatchable renewable units $d \epsilon D$ are modelled with a conversion process as detailed in *Equation 6.12*.

Equation 6.12 $$\boldsymbol{P_{d,t}} = \boldsymbol{\eta_d} \cdot \boldsymbol{h_{d,t}} \qquad \forall \boldsymbol{d} \in \boldsymbol{D}, \forall \boldsymbol{t} \in \boldsymbol{T}$$

The conversion process introduced the input of fuel $\boldsymbol{h}$, which can be bounded for the time horizon within *Equation 6.13*. This equation allows us to model annual resource limitation in biomass or waste.

Equation 6.13 $$\sum_{t\in T} \boldsymbol{h}_{\boldsymbol{d},\boldsymbol{t}} \cdot \boldsymbol{\tau} \leq \overline{h}_c \qquad \forall \boldsymbol{d} \in \boldsymbol{D}$$

to model the renewable energy penetration in the system by exogenously defined RE share, an additional constraint is introduced. The renewable energy share is defined within *Equation 6.14*. by the share of conventional technologies $c \in \mathbb{C}$.

Equation 6.14 $$\sum_{t\epsilon T} \sum_{c\epsilon\mathbb{C}} P_{c,t} \cdot \tau \leq \left(1 - RE^{share}\right) \cdot \sum_{\iota\epsilon L} c_l^{amount}$$

The excess supply within the model is limited by the two equations seen below. Equation limits the excess power in every time step by 10% of the peak demand d^{peak} of the year, while equation limits excess energy for the entire time horizon. This was critical to avoid excess power production as observed in other energy system models and investigations (Ćosić, Krajačić, and Duić 2012, 84–85; Gioutsos et al. 2018, 440). Notwithstanding some analysis was conducted by allowing between 70% - 100% overproduction in the system to examine the impact of cost on the final energy system

Equation 6.15 $$P_t^{excess} \leq 0.1 \cdot d^{peak} \qquad \forall t \in T$$

Equation 6.16 $$\sum_{t\in T} P_t^{excess} \cdot \tau \leq 0.1 \cdot \sum_{l\in L} c_l^{amount}$$

Chapter 7 – Creation of Oemof Barbados model and scenarios

7.1. The Oemof-barbados model

In this investigation, oemof-barbados model is used as an investment model that compares the value of various 100% RE mixes to cost-optimal dispatch options. The 100% RE scenarios were modelled simultaneously with the cost-optimal solution for the energy system. The model limited the theoretical maximal share of renewable energy in the system through the potentials of RE technologies in MW of installed capacity, potential storage capacities in MWh and the maximum allowed curtailment (energy and power). The theoretical maximal RE share for each scenario was retrieved using a set of constraints within the objective function that minimizes the sum of fossil fuel production. Using Equation 6.14 as shown in Chapter 6, the 100% RE scenarios were created, whereas the cost-optimal scenarios were modelled by omitting the same equation.

7.2. Creation of scenarios

As noted in Harewood et al. (2021, 128), the primary reference (REF) scenario is based on several sources, which included the following: the BLP-Integrated Resource Plan (IRP) (2014), the (IRENA) Energy Roadmap for Barbados (2016), the Barbados National Renewable Energy Policy (BNEP) (2019) and Electricity Market Study by Hohmeyer (2017). These policy documents specifically detailed the expected future demands, informed possible resource potentials for renewable resources, installed capacities for the conventional dispatch or possible technical storage potentials, in addition to the cost information, compulsory for the model. Harewood et al. (2021, 128) noted that some of these sources produced conflicting values for some of the parameters. For example, IRP (2014) of the BLP listed the installed capacity of primarily fossil fuel generators was 239.1 MW, whereas the IRENA report and Electricity Market Study stated that the installed capacities were 241.5 MW and 240 MW respectively. In addition, the expected installed capacities in the scenario timelines ranged from 2030 or 2036. The total installed capacities in the final year of timelines of the energy system were BL&P (293.3 MW), IRENA (450 MW) and Electricity study (395 MW). The main parameters of interest for the investigation were summarized as shown in Table 7.1.

Table 7.1. Summaries the main sources of data for the model researched from policy documents and studies (Andre Harewood, Hilpert, and Dettner 2021).

Category	BL&P IRP Report (BL&P 2014)	IRENA Roadmap for Barbados (IRENA 2016)	Electricity Market Study (Hohmeyer 2017)	Barbados National Energy Policy (GOB 2019)

Category	BL&P IRP Report (BL&P 2014)	IRENA Roadmap for Barbados (IRENA 2016)	Electricity Market Study (Hohmeyer 2017)	Barbados National Energy Policy (GOB 2019)
Curr. Installed capacity	239.1 MW (2012)	241.5 MW (2015)	240 MW	n/a
Exp. Installed capacity	293.3 MW (2036)	450 MW (2030)	395 MW	n/a
Curr. demand	980 GWh/a (2012)	n/a	912 GWh/a (2013)	11,297 BOE per day
Exp. Demand 2030	903-1986 GWh (2036)	998 GWh/a (2030)	1350 GWh/a	n/a
Curr. Generation	n/a	1092 GWh/a (2015)	970 GWh/a (2013)	n/a
Exp. Capacity	n/a	998 GWh/a	n/a	1600 GWh
Curr. Peak demand	163 MW (2011)	158 MW (2015)	150 MW	n/a
Exp. Peak demand	208.1 MW	145 MW	140 – 300 MW (2035)	n/a
Exp. Share of RE	1.2 - 29%	max. 76%	100%	76%
Exp. Storage	Wind with 10% battery	150 MW battery (2030)	3 GWh (PHS) (2035)	_
Exp. Biomass	25 MW	18 MW (for 100% 54 MW)	25 - 40 MW (35 GWh)	39 MW (2035)
Exp. Waste potential	60 MW (2035)	2.2 MW	11 MW	40 MW (WtE)
Exp. Solar (PV)	_	60 MW (2030)	219 MW – 265 MW	195 MW (2037)
Exp. Wind	_	15 MW (2030)	219 MW – 265 MW (2035)	127 MW (2037)
Exp. Natural gas	n/a	n/a	n/a	49 MW (3037)
Exp. Electrification rate vehicles	_	20% - 50% EV	100% EV	100% EV
Exp. Cruise ship demand		n/a	n/a	n/a

7.3. Installed capacities of renewables, storage conventional dispatch

Wind and solar renewable energy sources on the island were represented as volatile components whereas, bagasse, and waste were controllable units (c.f.Table 7.2.) The conventional dispatch combines low speed and medium speed plants powered by heavy fuel oil (HFO). Bagasse was the primary form of bioenergy used in the model, followed by the combustion of waste-to-energy represented as waste in the model. The selection of storage technologies was limited to pumped hydro storage and lithium-ion batteries as these were the primary forms of storage considered in previous scenario analysis (Hohmeyer 2017; IRENA 2016; GOB 2019). Based on the history of sugar cane production, bagasse utilization as an energy source was considered in the scenarios as noted by IRENA (2016, 29) and Hohmeyer (2017, 14). A series of maximum installed capacities and limits were optimized in the model based on the above-mentioned studies, as stated in Table 7.1 below, for the cost-optimal and 100% RE scenarios. In addition, the capacities of the conventional and dispatchable renewables, such as pump hydro power and batteries, were left open such that the model could select and optimize the installed capacities for the cost-optimal and 100% RE scenarios.

Table 7.2. Summarizes the installed capacities and technologies for the renewable energy sources used in the model (Andre Harewood, Hilpert, and Dettner 2021, 128).

Carrier	Technology	Installed cap (MW) / Storage capacity potential (MW/h)	Literature Source
wind	onshore wind	472 MW	**Hohmeyer (2017), Rogers (2017)**
solar	Solar PV distributed - (pv-distributed	234.1 MW	**Alleyne (2014) and Haynes (2019)**
	Solar PV utility (pv-utility)	80 MW	**Alleyne (2014) and Haynes (2019)**
lithium	battery	400 MWh	**Own Creation n.d based on Hohmeyer (2017)**
hydro	Pumped hydro storage	5000 MWh	**Own Creation n.d based on Hohmeyer (2017)**

Carrier	Technology	Installed cap (MW) / Storage capacity potential (MW/h)	Literature Source
	(phs)		
bagasse	Steam (st)	_	**BL&P (2014)**
waste	Steam (st)	_	**BL&P (2014)**
Diesel	Combine cycle gas turbine (ccgt)	_	**BL&P (2014)**
Heavy fuel oil (hfo)	Low speed diesel (lsd)	_	**BL&P (2014)**

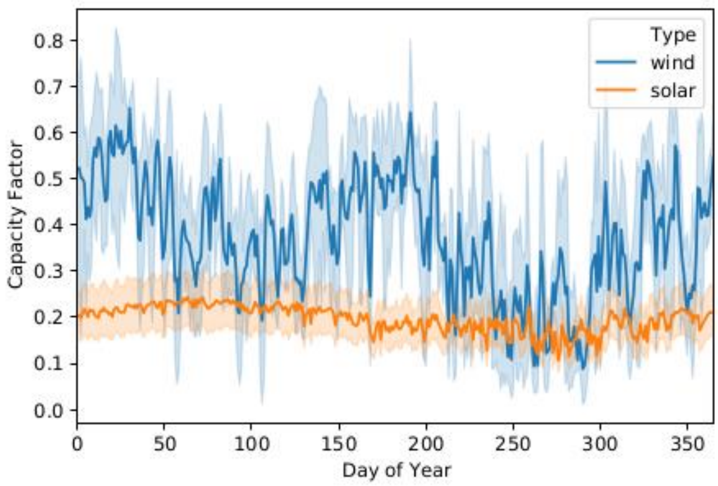

Figure 7.1. Summarizes the variation in the wind resource in comparison to the solar resource for the year (Andre Harewood, Hilpert, and Dettner 2021, 121).

7.4. Bagasse and Waste-to-energy

The main biomass resource was bagasse, which was modelled based on the BL&P (2014), IRENA (2016), and Hohmeyer (2017). As described in Harewood et al. (2021, 123) the bagasse annual potential was limited to 656 GWh. The biomass technology and resources considered for Barbados were direct combustion system of cane bagasse and river tamarind. Solid bagasse combustion from bagasse during the sugar cane harvest season and river tamarind for the rest of the year. As noted in Harewood et al. (2021, 128) conflicting sources of information are reported for the bagasse combustion project. For example, Hohmeyer (2017, 140) reports that the project was planned as a 22.5 MW combustion plant whereas, IRENA (2016, 128) noted that an 18 MW plant was expected to enter service in 2017, with the possibility of more plants. In addition, IRENA (2016, 36) noted that the 100% renewable energy scenario would require 54 MW, which requires 1.6 million tonnes of sugar cane per year grown on 20,000 hectares, which was only possible when half of the land mass was dedicated solely to sugar production, which peaked in 1967. The available land area for sugar cane production is one-eighth of the island. For this reason, IRENA (2016, 127) and the BL&P (2014, 92) supported the use of imported biomass/bioenergy resources. However, to date, no biomass plants have entered service.

As mentioned in Chapter 2, Barbados has a history of sugar cane production, which is continued at a loss to the industry but remains a vital source of foreign exchange. Therefore, there is interest in revitalizing the sector into a more economically viable product. The transition of the sugar industry to the combustion of bagasse has been the focus of successive Government administrations and regulatory agencies. The 100% RES or any energy system with high shares of renewable energy would require dispatchable and controllable resources that can be substituted for fossil fuel generation technologies. However, selecting bagasse and river tamarind is challenging in securing adequate domestic production of the local biomass resources, and there will be issues with the flexibility of biomass combustion powered by steam turbines to service the residual load. Bagasse combustion is simply not a highly flexible operation for power production, as the technology functions as a base load steam turbine.

Examining the use of bagasse for energy is a crucial aspect of the sugar industry's restructuring project, which has received support from multiple government administrations. Therefore, this study investigated the combination of bagasse and river tamarind; however, within the limitations of these technologies. Ultimately, the scenario analysis can highlight the importance of dispatchable renewable generation units to service the residual load and installed capacities required to support the 100% RES, which serves as a good start to discussions on the final energy system and paves the way for additional studies and investigations to examine to the role of bioenergy sources within the future 100% RES of Barbados.

Waste-to-energy was examined in the model based on Government plans to pursue technology to address waste management and improve energy security. As described in Harewood et al. (2021, 123) the theoretical potential of the waste to energy was 218 GWh in the model. The total annual waste received for landfilling in 2012 was estimated to be 352,026 tonnes a year, with a daily waste stream estimated to be 1,000 tonnes per day. The current Mangrove Pond Landfill is approaching maximum capacity and requires action by local authorities (Harewood et al. 2014). BL&P (2014, 92) recommended incineration via a boiler and turbine and plasma gasification waste-to-energy technologies. In addition, Hohmeyer (2017, 140) also examined the use of plasma gasification; however, both reports acknowledge that plasma gasification technology at the time was unproven and expensive compared to other options. For example, production of syngas from the plasma gasification of waste was possible but would increase overall system costs when the syngas is stored in larger volumes from the continuous plasma gasification process. More importantly, there are also issues with the flexibility and dynamic operation of a typical incinerator plant to service the residual load. Based on the Government plans at the time, within technological limitation, incineration was examined, to show how the technology would have to fit within the context of a 100% RES for Barbados.

7.5. Conventional Dispatch

The island’s sole electricity utility is the Barbados Light and Power CO. Ltd (BL&P) (GOB 2019). The 2015 generation mix was unchanged, with diesel gensets (113.3 MW) accounting for over half the supply, steam turbines (40 MW), and low-speed diesel and gas turbines (86 MW) (BL&P 2014b, 76; Haynes 2019). These are operated at three generating stations: Spring Garden, Garrison Hill and Seawell, as summarised in Table 7.3 below (BL&P 2014, 66). Spring Garden is the central generating station and has a maximum installed capacity of 153.1 MW. However, the company has 33 MW of flexible power plants at a new location in Trent's St Lucy (Wärtsilä 2020). The earliest retirement date for the steam turbines was in January 2017; however, these remain in use (BL&P 2014, 76).

The Seawell generating station is in the vicinity of the Grantly Adams International Airport, 12 km southeast of the central city, with a maximum installed capacity of 73 MW composed of gas turbines (BL&P 2014, 66). The Garrison Hill generating station is limited to a 13 MW gas turbine due for decommission in 2016 but remains in operation. The fuel source used as inputs for generation changes depending on the annual oil price and the degree of subsidization by the GoB (Haynes 2019). For this reason, heavy fuel oil (HFO) is the primary fuel source for all of the low-speed diesel units at the Spring Garden location (Espinasa et al. 2016, 9–10). Except for one unit, the gas turbines at the Garrison and Seawell sites were refurbished for diesel fuel operation instead of Jet-A1 fuel. In conclusion, much of the current power plant dispatch is still in use, even though several gensets are due decommission or will be within the next few years.

Table 7.3. Summary of dispatch by generating station (BL&P 2014, 68)

Power station	Genset	Fuel	Capacity (MW)	Generation type	Proposed decommission dates.
Spring Garden	S1	HFO	20	Steam turbine	2017-01-01
	S1	HFO	20	Steam turbine	2017-01-01
	D10	HFO	12.5	Low-speed diesel generator	2019-01-01
	D11	HFO	12.5	Low-speed diesel generator	2019-01-01
	D12	HFO	12.5	Low-speed diesel generator	2019-01-01
	D13	HFO	12.5	Low-speed diesel generator	2019-01-01
	CG01	HFO	1.5	Co-generation unit	2019-01-01
	CG02	HFO	2.2	Co-generation unit	2019-01-01
	D14	HFO	29.7	Low-speed diesel generator	2036-01-01
	D15	HFO	29.7	Low-speed diesel generator	2036-01-01
Seawell	GT03	Diesel	13	Gas turbine	2022-01-01
	GT04	Diesel	20	Gas turbine	2025-01-01
	GT05	Jet-fuel	20	Gas turbine	2027-01-01
	GT06	Diesel	20	Gas turbine	2028-01-01
Garrison Hill	GT02	Diesel	13	Gas turbine	2022-01-01

[3]

As most of the current conventional dispatch is due for decommission, based on recommendations of the BL&P (2014, 75–76) and IRENA (2016, 114) a combination of newer of medium speed diesel (msce) and low speed diesel (lsce) gensets were recommended for the future energy system, which were modelled for the cost-optimal renewable energy scenarios as shown in Table 7.4 below.

7.6. Scenarios

Using the information from the studies above, several scenarios were created as shown below in Table 7.4. The scenarios were grouped into 4 main categories as follows:

[3] The information was compiled from the Integrated Resource Plan (IRP) report of the Barbados Light and Power (BL&P 2014). Based on meetings with the Energy Division, the information was updated for 2021.

- General scenarios with included the reference (REF) and status quo (SQ) scenarios.
- Technology scenarios which included the High demand (HD), Restricted biomass (RB), Reduced wind increased solar potentials (SRW), high wind and solar potentials (HSW) and No pumped hydropower storage - PHS (NPHS) scenarios.
- Cost variation scenarios which included the High bagasse investment costs (HBC) and Low oil price costs (LOP) scenarios.
- Vehicular transport scenarios which included the Electric vehicle uncontrolled charging uc (EVUC); High electric bus uncontrolled charging and high Electric vehicle-controlled charging (HBCC); High electric bus uncontrolled charging and high electric vehicle uncontrolled charging.

The (REF) scenario considered the most relevant aspects for the future Barbadian energy system as described in Harewood et al. (2021, 123), which according to the Government of Barbados (2019, 77), remains attaining a 100% RES by 2030, with a base demand (943 GWh), EV demand using controlled charging (265 GWh) and cruise demand (44.25 GWh) which was justified in Section 7.7.3 and summarized in Table 7.4 below. The status-quo (SQ) scenario was for comparison with the REF scenario, which only considered the energy generation demand (943 GWh), excluding the electrification of the cruise and passenger transportation sectors.

The technology and resource-based scenarios tested technology and resource potentials on the future energy system as follows in Table 7.4 below – High demand (HD), Restricted biomass (RB), Reduced wind increased solar potentials (SRW), high wind and solar potentials (HSW) and No pumped hydropower storage - PHS (NPHS). The cost variation scenarios examined various resource costs on the future energy system: High bagasse investment costs (HBC) and Low oil price costs (LOP). The passenger transportation scenarios were created based on Harewood et al. (2021) with the addition of scenarios that examined the effect of electric vehicle bus fleet on the Barbadian energy system.

Table 7.4. Summaries the main scenarios examined in the oemof-barbados model (Andre Harewood, Hilpert, and Dettner 2021, 123) *and Own Creation n.d)*

Variation	Scenario	Symbol	Parameter	Value
General	Status-quo	SQ	Based demand	943 GWh
	Reference	REF	Base demand, EV demand, controlled charging, Cruise demand	943 GWh 265 GWh 44.15 GWh
Technological and resource-based	High demand	HD	Based demand + 1.2%/a	1,321.3 GWh

Variation	Scenario	Symbol	Parameter	Value
	Restricted biomass	RB	Biomass potential - 50% Waste potential - 50%	328 GWh 109 GWh
	Reduced wind increased solar potentials (Solar PV – utility)	SRW	Wind resource potential – 50% Solar resource + 50%	166 MW Solar PV – utility (250 MW) Total Solar PV resource (450 MW)
	High wind High solar PV	HSW	Wind resource Solar resource + 50%	472 MW Solar PV – utility (250 MW) Total Solar PV resource (450 MW)
	No PHS	NPHS	No pump hydro storage	–
Passenger transportation	Electric vehicle uc	EVUC	High EV demand, uncontrolled charging	265 GWh
	High electric bus uc Electric vehicle cc	HBCC	High battery-electric bus demand and High EV demand-controlled charging	176.68 GWh 265 GWh
	High electric bus uc and electric vehicle uc	HEU	High E-bus demand, uncontrolled charging and High EV demand, uncontrolled charging	176.68 GWh 265 GWh
Cost variations	High bagasse investment costs	HBC	Higher bagasse investment costs	18400 $/kW
	Low oil price costs	LOP LRC	Oil price costs -50% Long term wind costs Long term PV distributed costs Long term PV utility costs	59.2$ /kWh 2900 $/kWh 2100 $/kWh 1500 $/kWh

7.7. Information used to create scenarios and scenario assumptions

7.7.1. Cost information for the model

The cost information used in the model was calculated in BBDs and the significant cost information for the resources and technologies for the model were abbreviated from several literature sources. The general cost information for the model includes capital expenditure (capex), weighted average cost of capital (wacc), fixed operation costs (fom), variable costs (vom) and availability factor (avf) and lifetime for all the components as shown in the Table 7.5.

Table 7.5. Summary of cost information used in the model (Own Creation n.d) .

carrier	tech	Tech scenario	capex	lifetime	wacc	efficiency	storage capex	fom	vom	avf	source
wind	onshore	reference	3500	20	0.07	1		0.04	0	1	IRENA 2016, p117, *Own Creation n.d*
solar	pv-distributed	reference	5400	20	0.07	1		0.01	0	1	IRENA2016, p117, , *Own Creation n.d*
solar	pv-utility	reference	3900	20	0.07	1		0.01	0	1	IRENA 2016, p117, , *Own Creation n.d*
lithium	battery	reference	100	12	0.07	0.948683	600	0.03	0	1	Mongrid (2019), converted to BB$
hydro	phs	reference	5000	45	0.07	0.894427	0	0.01	0	1	Mongrid (2019), converted to BB$
diesel	ccgt	reference	3698	25	0.07	0.473909		0.029757	10	0.895	BL&P (2014 p. 68)
diesel	ocgt	reference	2261	20	0.07	0.328628		0.011517	80	0.914	BL&P (2014 p. 68)
hfo	lsce	reference	2853	30	0.07	0.463732		0.040294	12	0.869	BL&P (2014 p. 68)
hfo	msce	reference	2344	25	0.07	0.438635		0.070392	18	0.839	BL&P (2014 p. 68)
gas	ccgt	reference	3129	25	0.07	0.476423		0.035168	10	0.895	BL&P (2014 p. 68)
gas	ocgt	reference	2269	25	0.07	0.32958		0.004866	80	0.914	BL&P (2014 p. 68)
gas	lsce	reference	3261	30	0.07	0.463732		0.035253	12	0.839	BL&P (2014 p. 68)
gas	lsce	reference	2649	25	0.07	0.445507		0.062288	18	0.829	BL&P (2014 p. 68)
bagasse	st	reference	8000	25	0.07	0.252751		0.03125	15	0.767	BL&P (2014, p.92)

carrier	tech	Tech scenario	capex	lifetime	wacc	efficiency	storage capex	fom	vom	avf	source
waste	ocgt	reference	18000	20	0.07	0.341214		0.038889	15	0.917808	BL&P (2014, p.92)

N:B. Fixed operation and maintenance costs (fom), variable operational and maintenance costs (vom), availability factor (avf), Weighted average cost of capital (wacc). All costs are in Barbadian currency BBD.

In the case of wind and solar resources, these costs were estimated based on IRENA (2016, 23), that was sourced from internal IRENA databases. In addition, the cost information used in the IRENA Roadmap for Barbados (2016, 23–24) was updated to represent better the local cost of renewable energy technologies. A major factor that impacts the costs to purchase renewable energy technologies is importation costs, as in the case for wind and solar energy technologies that would have to be imported to the island for installation, in addition to the global price of renewable technologies internationally. For example, according to BL&P (2014, 92) the fixed operation costs for solar PV were about 79,000 BBD MW/year and 55,000 MW/year for wind, which the BL&P later revised to 65,000 MW/year (solar PV) and 115,000 MW/year (wind). In the cases of solar, the reduction in cost reflects a decrease in the cost of solar PV worldwide in addition well established supply chains for the technology locally. In the cases of wind, the increase in costs can be attributed to the high cost of both importation and installation of wind energy technology on the island, that is unique to Barbados.

The cost of bioenergy and waste-to-energy was taken from BL&P (2014, 92) based on projects recommended by the BL&P to the GoB. At the time of the data collection, this information was the most recent; the GoB also validated this information during interviews, which recommended using this specific cost information for this investigation. In addition, the study focused on bagasse as a by-product of sugar production, supplemented with river tamarind; cost information was focused on these resources. Imported biomass is also possible for the Barbadian energy system, but costs would be three to five times the costs of locally produced biomass; however, whether these resources were imported from within the region or from international sources needed to be clarified. For example, Clarke (2016) proposed that regional trade of biomass resources from within Guyana should lead to affordable biomass resources for the Caribbean region, including Barbados. Based on IRP (2014, 46) and Haynes (2019, 123) for the cost variation scenario (HBC) a higher bagasse investment costs of 18400 $/kW were used based on the estimates provided by the GoB as noted by Hohmeyer (2017, 71–72). For the low oil price (LOP) scenario is reduced cost of 59.2$ /kWh (hfo) and 76.8 /kWh (diesel) were used for Barbados based on the IRP (2014, 36–38) and IRENA (2016, 31).

7.7.1.1. Assumptions to create the cost scenarios

Based on a discussion with BADMC, a high bagasse investment cost of 460 Mio. BBDS from the Electricity market study was used to estimate the higher biomass cost of 18400 BBD$/kW (Hohmeyer

2017, 71). Similarly, based on the IRENA Report for Barbados, a low oil price of 59.2 BBD$7kWh was used for the model (IRENA 2016, 31). Ultimately, a 50% reduction in the price is highly unlikely for the Barbadian energy system in the future due to more global economic events and the nation's SID state characteristics, but this is useful for discussion regarding the future energy system and scenario analysis. The low renewables cost information was based on a lower range of costs provided on solar PV and wind resources in the IRENA Roadmap for Barbados (IRENA 2016, 31).

7.7.2. Creation of the passenger transportation scenarios

Regarding critical energy consuming sectors, Masson and Perez (2021) highlighted that Barbados has the highest penetration of e-mobility for passenger transport in the Caribbean. The Nissan Leaf battery-electric is among the most popular, modelled in the scenario analysis. Consequently, the controlled charging demand of passenger transport using an EV leaf as a model and an electrifying rate of 80% was examined for the investigation with a demand of 265 GWh as summarized in Table 7.4. Based on the importance of the tourism sector for economic activity, shore-to-ship charging was addressed in scenario analysis with a demand of 44.15 GWh, as summarized in Table 7.4.

Several specific scenarios, examined the electrification of the public sector bus fleet and passenger transport using a combination of controlled and uncontrolled charging demand profiles shown in Table 7.4 as follows: Electric vehicle uc - 265 GWh (EVUC); High electric bus uc - 176.68 GWh and Electric vehicle cc - 265 GWh (HBCC); High electric bus uc and electric vehicle uc (HEU). The same electricity generation and cruise tourism demand was utilized in all vehicular transportation scenarios. The (EVUC) examined the impact of uncontrolled charging of passenger transport compared to the REF scenario. The effects of uncontrolled battery electric bus fleet charging were compared in the HBCC and HEU, which examined the impacts of controlled and uncontrolled passenger transportation, respectively.

7.7.3. Creation of the Demand for the scenarios

As stated by Harewood et al. (2021, 123) the total future demand for 2030 was set at 943 GWh in the REF scenario, which was current demand in 2019; this was considered a reasonable assumption for several reasons. The proposed reference case from BLP (2014) used a growth rate of 1.2% annually from 2011, which forecasted the demand to reach 1,200 GWh in 2019. However, the actual demand showed a marginal increase from 912 GWh in 2013 to 943 GWh in 2019. Most of the other studies are based on these predictions, which overestimated the growth in demand in those proposed timelines; also, none of the forecasted growth rates decoupled the transportation sector from the annual demand. Harewood et al. (2021, 123) noted that a only a slight increase in the demand should be expected from the other economic sectors such as construction, industrial, agriculture, commercial and residential. Also, for the future 2030 energy system, the GOB intends to aggressively pursue renewable energy and energy conservation measures for the residential and commercial sectors, as outlined in the BNEP (2019, 75). BL&P (2014, 23–25) showed that commercial and industrial demand peaked only in 2007, with significant economic activity due to a boom in the construction industry. However, the Government of Barbados has no specific intentions to pursue significant industrial development, nor are major construction projects expected to reach those historical peaks.

Economic recovery in Barbados has been challenged by the poor economic performance of international markets such as the US and UK, both major trade partners that significantly contribute to the Barbados tourism industry (Espinasa et al. 2016, 5–7; Andre Harewood, Hilpert, and Dettner 2021, 120–21; United Nations 2021, 2–3). More recently, there has been a substantial drop in demand from all economic sectors due to a decline in economic activity because of the COVID-19 pandemic, which is expected to impact the country until 2023 and well into the future (Leal Filho et al. 2020). By the latest estimates for 2022 have shown that tourism has only slightly recovered but not to pre-pandemic levels of 2019 (IMF 2023). Consequently, the base demand in the REF scenario was used in all scenarios, except for the high demand (HD) scenario. In the HD scenario, growth in residential, commercial, and industrial demands was expected to occur annually by 1.2% between 2012 to 2030, which is a reasonable assumption based on the best case possibility of increased business and economic development in these sectors, as theorized by BL&P.(2014, 27). Consequently, by 2030 the annual demand was estimated to reach 1,321.3 GWh (2030) (Andre Harewood, Hilpert, and Dettner 2021, 123).

7.8. Hourly load profiles

Installed wind and PV power generators were modelled using the renewables.ninja online platform based on the technical specifications and spatial distribution of the specific generation technology in addition to past weather information (Staffell and Pfenninger 2018). The renewables.ninja generates hourly times series from the geographical locations of individual wind and solar installations aggregated at a national level. Based on Rogers (2017, 8), GIS locations were mapped in QGIS for various wind farm installation zones. However, only one of the zones in the North was used in the oemof-barbados model as this was most probable site for successful wind farm installation in comparison to other locations based on the Governments policy regarding the expansion of wind. In addition, the model aggregated the electricity production from the wind energy sites, therefore, the best site was selected. Nonetheless, the wind zones were considered in the PyPSA-barbados model as specific sites of variable renewable energy generation. The technical specifications for these generators were summarized as shown in Table 7.5 above.

7.8.1. Transportation demand profiles

- Electric passenger vehicle demand

As noted in the BNEP (2019), the Government of Barbados intends to pursue complete electrification of vehicular transportation. Passenger vehicles comprise 81% of vehicular transport, thus, the analysis focused on the demand from these vehicles in addition to electrifying the bus fleet. The controlled (cc) and uncontrolled charging (uc) demand from E-mobility was considered in three separate scenarios as follows: high electric passenger vehicle uc (EVUC); High E-bus uc with high passenger vehicle cc (HBCC) and High electric bus uc with high Electric passenger vehicle uc (HEU).

All the scenarios except the SQ, EVUC and HEU utilized the controlled charging demand profile of a sampled Nissan Leaf battery-electric vehicle. Figure 7.2 and Figure 7.3 below showed the demand profiles of both the controlled passenger EV charging and uncontrolled passenger EV charging as sampled from the BL&P (2013) and IRENA (2016). The uncontrolled charging profile was created by allowing charging to peak around 18:00 hrs., in the evening. when most of the public would be home during an average workweek. Whereas, for the controlled charging, the peak charging was allowed to occur around 12:00 hrs. to peak with solar PV charging.

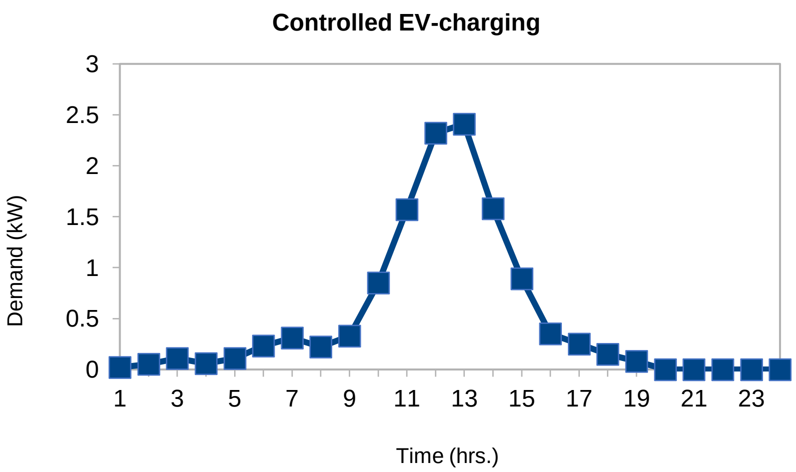

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Figure 7.2. Summarizes the controlled charging profile for passenger EV used in the model (Andre Harewood, Hilpert, and Dettner 2021).

[44] The load profile was simulated from raw data collected an E-mobility pilot project of the BL&P and IRENA Roadmap.

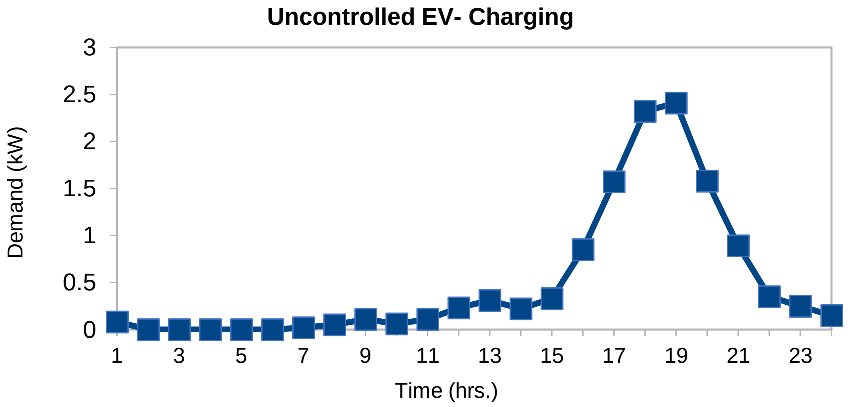

Figure 7.3. Summarizes the uncontrolled charging profile for a passenger EV used in the model (Andre Harewood, Hilpert, and Dettner 2021).

- Battery electric bus fleet demand profile

The Government of Barbados maintains a fleet of battery-electric buses charged at the three charging stations at Weymouth, Mangrove and Speightstown transportation depots (Haynes 2021a, 123). Based on interviews with energy sector stakeholders the fleet comprised 33 buses from July to September 2020, which increased to 35 buses between December to February 2021, with a final increase to 49 buses between September and October 2021. Most of the buses are located at Weymouth, Mangrove, and Speightstown. Energy stakeholders managing the bus fleet's charging data were concerned about data privacy. To protect data privacy, the specific bus depots was anonymized as A,B and C in Figure 7.5 and Figure 7.4. Based on stakeholder interviews, an estimate of the charging profiles at each depot, shown in Figure 7.4 and Figure 7.5., were recreated for the investigation. The data in Figure 7.4 shows during the period of May 2021 to August 2021 the demand slightly changes with the highest demand corresponding to January 2021

Figure 7.5 shows that most of the charging peaked at 21:00 hrs. to 02:00 hrs., reaching a maximum around 23:00 hrs., which corresponds to the most convenient time for charging the bus fleet. Depot A and B have the most significant charging demand. However, more information was required to determine if this was due to more frequent use of the buses or more of the E-Bus fleet located at these charging stations.

At the time of this investigation, only the demand profiles could be recreated, and other studies or information regarding the demand and use of electric buses were in the planning phases or unavailable for analysis. The charging profiles for the three bus depots were combined to form the electric bus uncontrolled charging (ebuc) profile for the entire year. The charging profile was considered uncontrolled as there was no intention to sync charging the bus fleet based on grid considerations or synchronize the charging with renewable resources considered. Instead, the authorities charged the buses when not in use. More information regarding the service of public bus routes was required to determine a feasible controlled charging schedule for the buses. Therefore, the investigation did not examine the controlled charging of electric buses, specifically with solar resources, at the time of modelling. The growth in the demand for E-buses was considered to reach a maximum of about 350 buses.

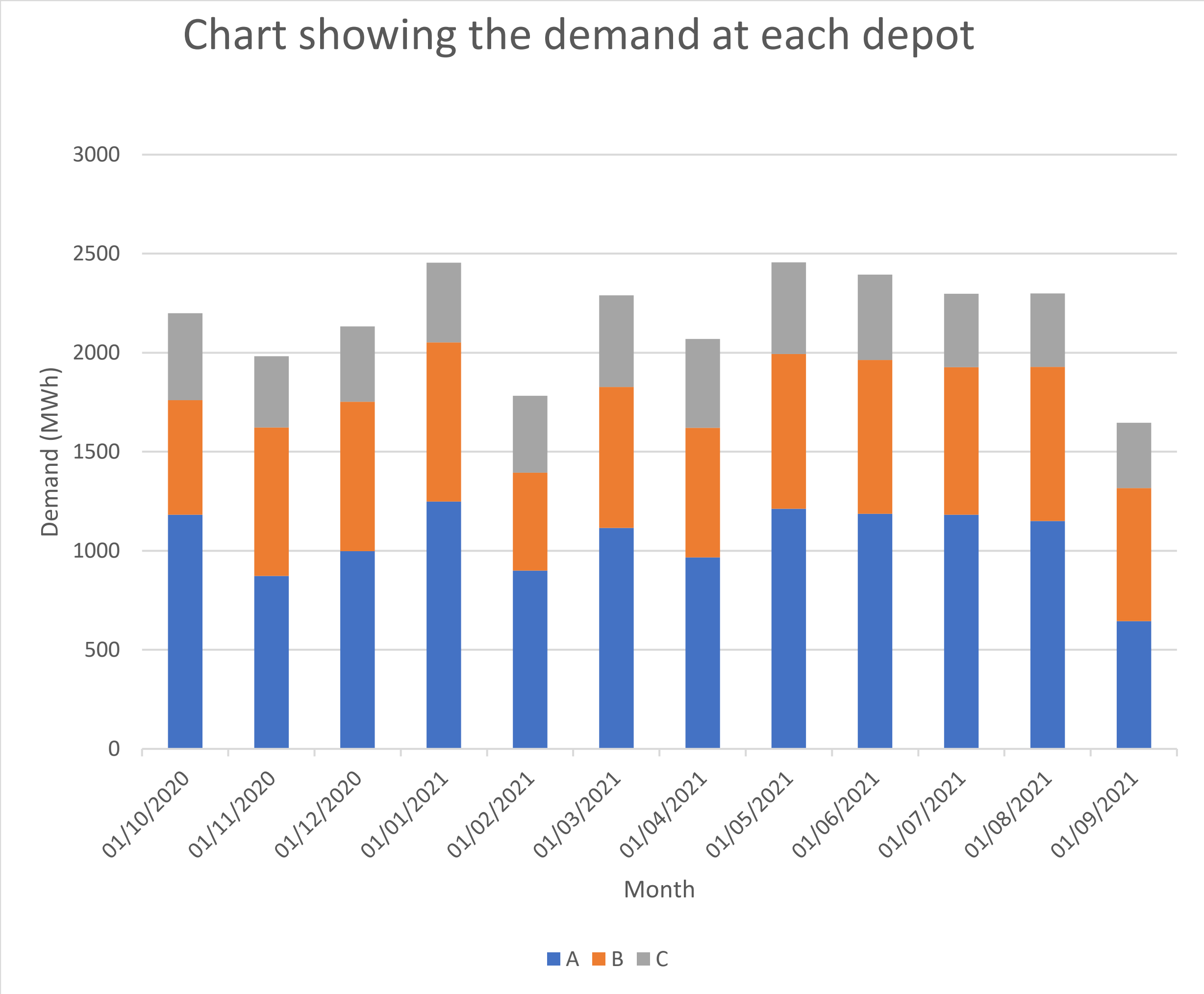

Figure 7.4. Summarizes uncontrolled charging of the E-bus fleet at the various Bus Depots (Haynes and BL&P 2021)

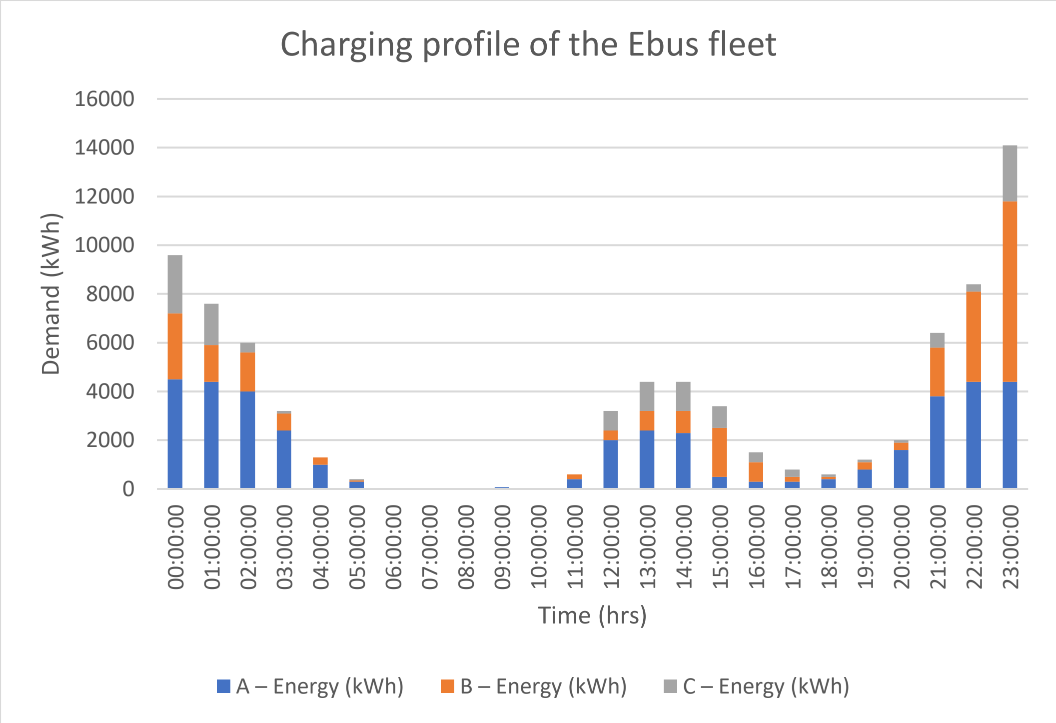

Figure 7.5. Summaries the charging profile for the E-bus fleet in 24 hours (BL&P 2021).

- Cruise-ship demand profiles

No information was publicly available regarding cruise ship demand profiles specifically for Barbados; therefore, a theoretical load profile was constructed. As shown in Figure 7.6 below, most ships docked in the harbor around 05:00 hrs. and 10:00 hrs. but 50% remained docked for 10 to 12 hours at a time. Consequently, a theoretical 12-hour demand profile representing the docking time of one cruise ship, as described by Hoyte (2016), was created to simulate an annual load profile using the 2018 arrivals from the Barbados Port Inc (2020). The data shows that the tourist season runs from mid-December to mid-April of the following year. Interestingly, the peak wind speeds coincided with the peak seasonal tourism demand seen by comparing Figure 7.1 and Figure 7.6.

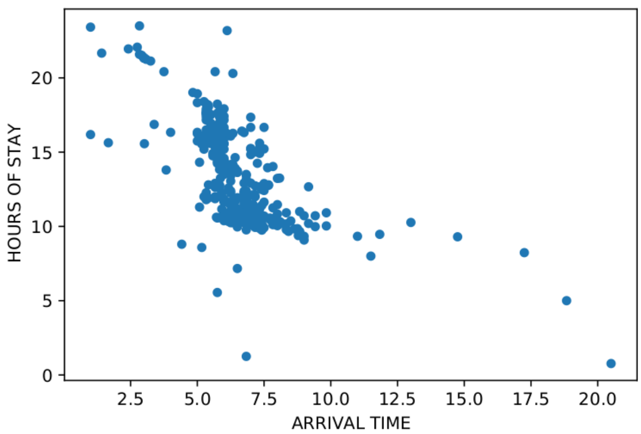

Figure 7.6. Describes the arrival time of cruise ships in comparison to length of time docked in the port for 2018 (Andre Harewood, Hilpert, and Dettner 2021).

As described in Harewood et al. (2021, 123), considering the length of time ships docked in the Port and Wang et al. (2015), the maximum demand of a ship was estimated to be 12 MW, but 15 MW was used to avoid underestimating the demand. This is a fair assumption for the scenario, as cruise ships are progressively increasing in size and length. The Port has plans to expand the berthing capacity, thereby increasing the size of vessels that can dock at a time. Thus, the seasonal pattern for the cruise ship industry was created and shown in Figure 7.7 below.

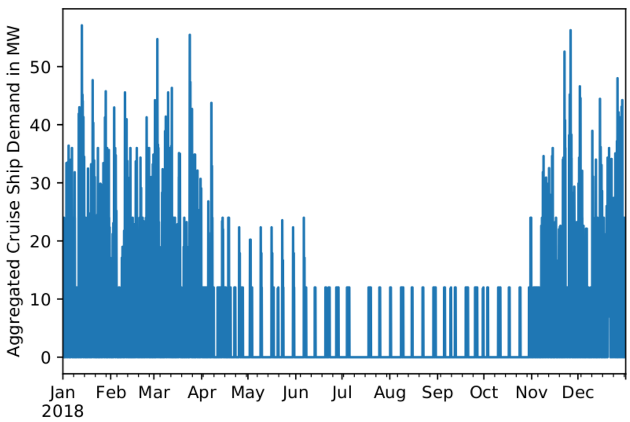

Figure 7.7. Describes tourism arrivals over the course of the year 2018 (Andre Harewood, Hilpert, and Dettner 2021).

7.9. Storage

The storage was defined as the storage capacity potential, the maximum allowed storage capacity of an energy storage *n*, per time timestep *t*. Half the initial capacity for the storage unit in the model was used in all the scenarios. The flows and storage capacity were connected such that a ratio of input and output flows were fixed as 0.25 and 0.0625, respectively. These ratios were selected based on the operation of pump storage facilities in Europe (Simon Hilpert and Harewood 2021). These ratios were the only ratios available in literature. The model code and framework were designed dependent on this ratio to optimize the PHS. Without more detailed information such as the turbine and reservoir dimensions as stated secondary reports in the Electricity Market study by Hohmeyer (2017, 260), deriving more accurate ratios for Barbados was not possible at the time of modelling.

Chapter 8 – Oemof-barbados model results

For convenience and ease of access the scenarios as listed in Chapter 7 page 77 to 78 in Table 7.4 were listed for reference viewing below.

Table 8.1. Summaries the main scenarios examined in the oemof-barbados model (Andre Harewood, Hilpert, and Dettner 2021, 123) *and Own Creation n.d)*

Variation	Scenario	Symbol	Parameter	Value
General	Status-quo	SQ	Based demand	943 GWh
	Reference	REF	Base demand, EV demand, controlled charging, Cruise demand	943 GWh 265 GWh 44.15 GWh
Technological and resource-based	High demand	HD	Based demand + 1.2%/a	1,321.3 GWh
	Restricted biomass	RB	Biomass potential - 50% Waste potential - 50%	328 GWh 109 GWh
	Reduced wind increased solar potentials (Solar PV – utility)	SRW	Wind resource potential – 50% Solar resource + 50%	166 MW Solar PV – utility (250 MW) Total Solar PV resource (450 MW)
	High wind High solar PV	HSW	Wind resource Solar resource + 50%	472 MW Solar PV – utility (250 MW) Total Solar PV resource (450 MW)
	No PHS	NPHS	No pump hydro storage	–
Passenger transportation	Electric vehicle uc	EVUC	High EV demand, uncontrolled charging	265 GWh
	High electric bus uc Electric vehicle cc	HBCC	High battery-electric bus demand and High EV demand-controlled charging	176.68 GWh 265 GWh

Variation	Scenario	Symbol	Parameter	Value
	High electric bus uc and electric vehicle uc	HEU	High E-bus demand, uncontrolled charging and High EV demand, uncontrolled charging	176.68 GWh 265 GWh
Cost variations	High bagasse investment costs	HBC	Higher bagasse investment costs	18400 $/kW
	Low oil price costs	LOP	Oil price costs -50%	59.2$ /kWh
	Low renewables costs	LRC	Long term wind costs Long term PV distributed costs Long term PV utility costs	2900 $/kW 2100 $/kW 1500 $/kW

8.1. Demand profile analysis

Figure 8.1 shows the demand in the REF- scenario as follows: the general electricity demand (el-demand); the demand from the cruise ships (cruise-demand) and passenger electric vehicles (evcc-demand). The Figure shows that the seasonality of the cruise ship demand significantly impacts aggregated demand.

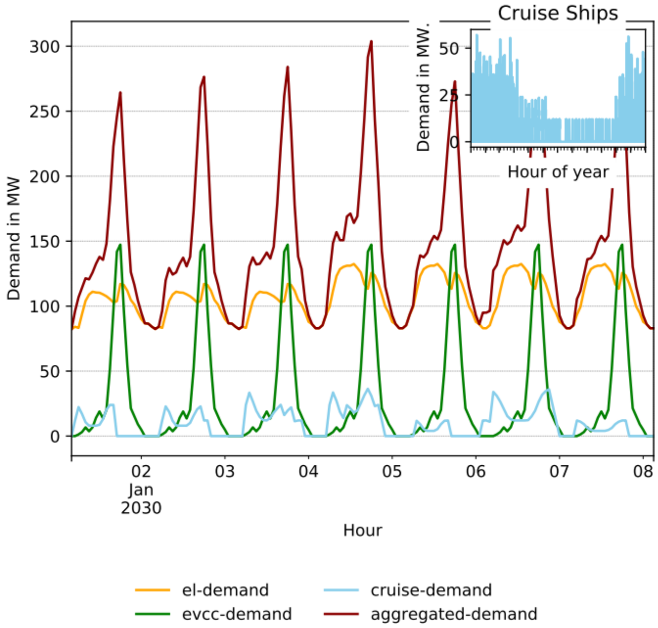

Figure 8.1. Summarizes the demand profiles examined in the oemof-barbados model with controlled passenger EVs and cruise ships (One Creation n.d).

Similarly, Figure 8.2 shows the addition of the E-bus uncontrolled charging of E-buses (ebus-demand) on the electricity demand modelled in the REF-scenario. The Figures support that the uncontrolled charging on the E-bus fleet significantly impacts the aggregated demand by creating another demand peak in the evening. Finally, Figure 8.3 shows the impact of uncontrolled charging on both the passenger transport vehicles and bus fleet, which shifts the peak demand to the evening in comparison to the REF scenario.

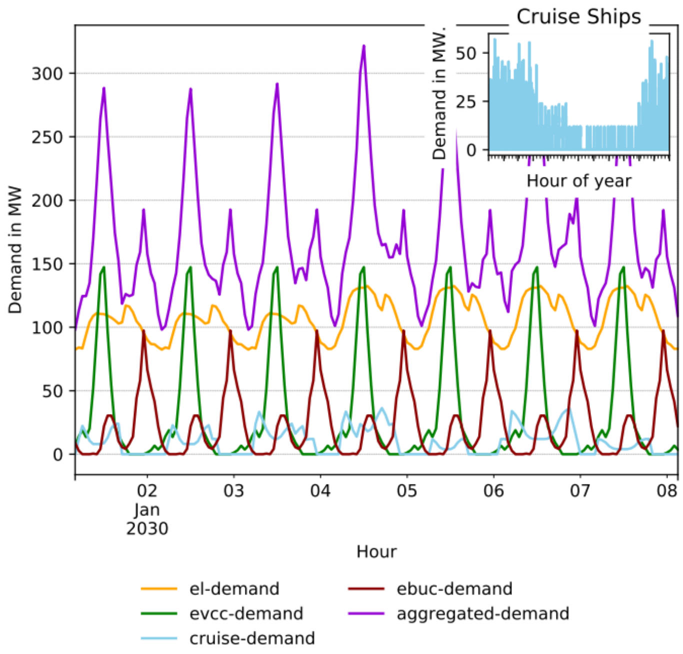

Figure 8.2. Summarizes the demand profiles examined in the oemof-barbados model with cruise ships, controlled passenger EVs and the uncontrolled charging of the E-bus fleet (Own Creation n.d).

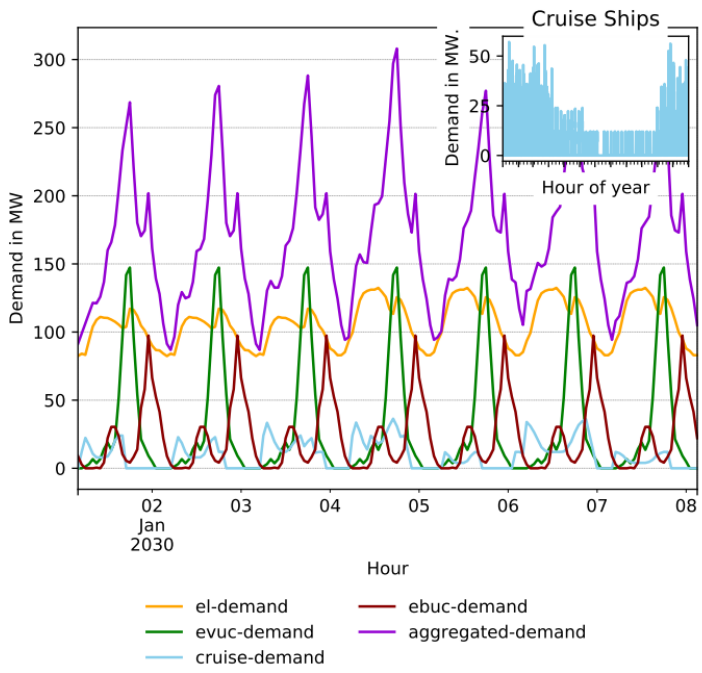

Figure 8.3. Summarizes the demand profiles examined in the oemof-barbados model with uncontrolled passenger EVs and the uncontrolled charging of the E-bus fleet (Own Creation n.d).

8.2. Scenario analysis and optimization

As explained in Chapters 7, the scenarios were based on Harewood et al. 2021. At the time of the investigation, the solar PV utility was capped at 80 MW, with a maximum solar PV distributed around 236 MW, which 'was deemed acceptable for the investigation based on the goals of the Energy Division and policy documents such as the BNEP and IRENA Roadmap for Barbados. However, based on more recent discussions with the Energy Division and energy sector stakeholders, the role of solar PV utility was further examined using the same scenarios but with the removal of the 80 MW cap on solar PV utility. The solar PV utility was increased to 400 MW, which represented an increase in cheaper solar resources in all scenarios. As observed below, the model optimized the system installing no solar PV distributed, due to the lower costs of the solar PV utility. Ultimately, these additional scenarios were examined in the investigation to generate discussions on possible futures for the Barbadian energy system. However, a complete reliance on solar PV utility is not necessarily ideal for the Barbadian energy system, considering the role of solar PV distributed in garnering public participation in the energy transition to a 100% RE system. Therefore, scenarios that examined combinations of solar PV distributed and utility were examined in sections 8.11, as a form of sensitivity analysis to understand the critical points at which the model optimized the energy system without solar PV distributed.

8.3. Comparison of scenarios with and without the 80 MW cap on the solar PV utility

8.3.1. Installed capacities

Harewood et al. (2021) described that with the solar PV utility limited to 80 MW, the renewable energy potential comprised a substantial share of the installed capacities regardless of the cost-optimal or the 100% RE scenarios. The cost-optimal scenarios have high renewable energy shares above 79%, except for the LOP (46%), HEU (76%) and HBC (68%) as shown in Figure 8.4 and summarized in Table 8.2. Based on the capacity factor of the wind resource compared to the other renewable resources, large capacities of wind are installed, and the demand is covered by wind, followed by conventional dispatch. The wind resource has the highest installed capacities for all the 100% RE scenarios except for SRW-100 (166 MW) and the LRC-100 (216.54 MW). In addition, higher conventional capacities were required in the REF scenario (66.75 MW lsce) and (102.34 MW msce) in comparison to the SQ scenario (51.76 MW lsce) and (24.59 MW msce). An additional 46.03 MW of PHS was required for the REF scenario compared to 18.36 MW in the SQ scenario.

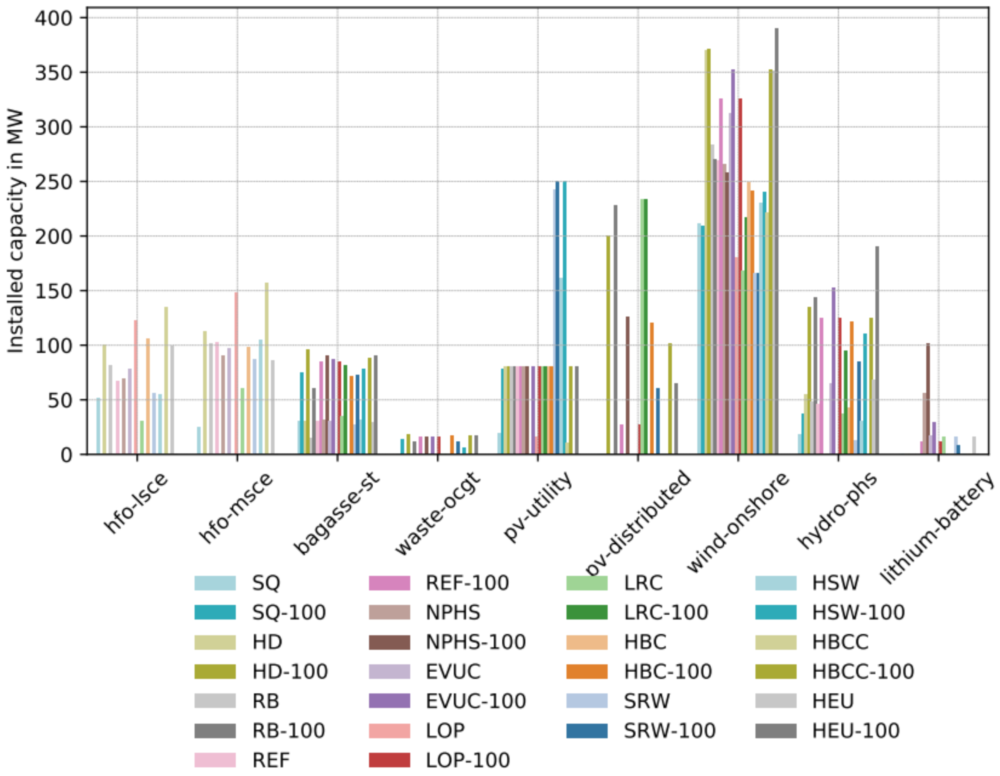

Figure 8.4. Summarizes the installed capacities of various generators for the scenarios examined in the oemof-barbados model (Own Creation n.d).

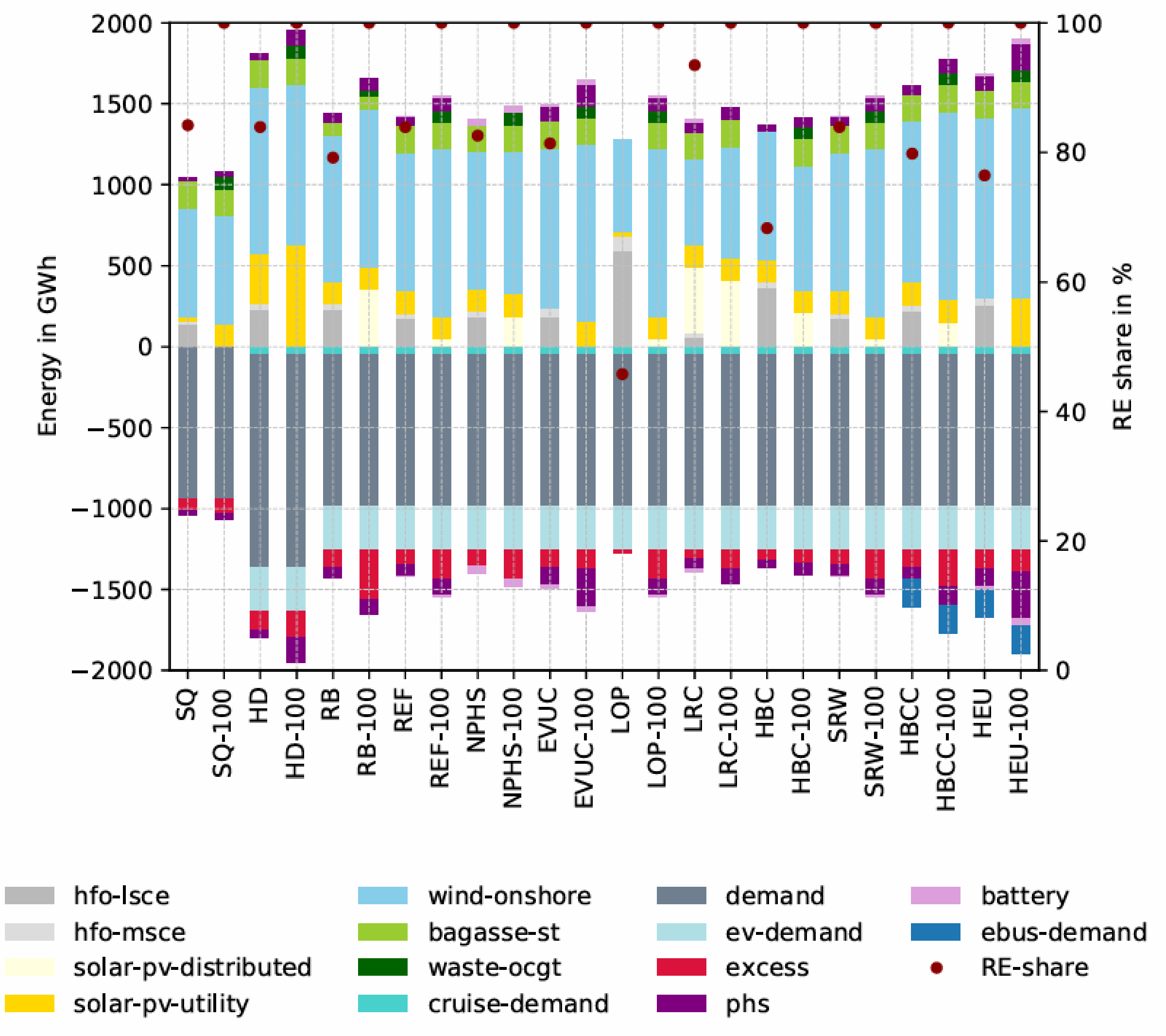

Figure 8.5. . Summarizes the share of renewable energy in the various scenarios examined in the oemof-barbados model (Own Creation n.d).

Solar PV utility has the highest installed capacity, with the removal of the 80 MW cap in 100% RE scenarios, specifically, with the highest solar PV resources installed at the utility scale in the LRC-100 (449.45 MW), HD-100 (373 MW) and HBCC-100 (289 MW). Notwithstanding the removal of the 80 MW cap on the Table 8.2 below, there was a slight reduction in the installed capacities for the conventional dispatches for the cost-optimal scenarios, as shown in Table 8.2 below.

Table 8.2. Comparing the installed capacities with and without the 80 MW cap on the Solar PV utility (Own Creation n.d)

Technology (MW) [5]	**Bagasse**		**HFO-lsce**		**HFO-msce**		**Hydro-phs**		**Lithium-battery**		**PV-distributed**	**PV-utility**		**Wind**		**Waste-ocgt**	
Scenario	Cap	No-cap	Cap	No-cap	Cap	No-cap	Cap	No-cap	Cap	No-cap	Cap	No-cap	Cap	No-cap	Cap	No-cap	Cap
EVUC	30	30	78.51	78.51	97.02	97.02	64.74	64	16.9	16.9	0	0	0	312.27	312.27	0	0
EVUC-100	87	86	0	0	0	0	152	144	29.76	39.56	0	92.57	80	341	352	16.03	16.22
HBC	0	0	105.53	73.28	98.35	46.31	43	37	0	19.71	0	319.16	80	160	249.81	0	0
HBC-100	72	67	0	0	0	0	121	78	0	0	120.5	385.42	80	124.27	124.27	14.11	16.68
HBCC	30	30	83.2	76.51	106.36	100.09	46	41	0	0	0	125.64	80	297.13	315.5	0	0
HBCC-100	88	86	0	0	0	124.55	124.55	98	0	0	101.45	289.04	80	265.78	353.77	15.24	16.81
HD	30	31	100.78	86.6	113.12	112.64	54	36	0	0	0	176.08	80	325.8	369.6	0	0
HD-100	96	96	0	0	0	0	134	93	0	0	200.78	373.03	80	302.9	371.33	16.16	17.98
HEU	29	29	98.95	98.95	85.49	85.49	68	68	16.21	16.21	0	0	0	352.1	251.13	0	0
HEU-100	90	88	0	0	0	0	190	160	0	31.82	65.18	171.16	80	369.48	389.8	16.61	17.25
HSW	31.21	_	55.21	_	105.23		30	_	0	_	0	_	161	_	230.24	_	0
HSW-100	80.1	_	0	_	0	_	96	_	0	_	0	_	309.5	_	212.73	_	1.53
LOP	0	0	122.92	122.9	148.34	148.35	0	0	0	0	0	16.24	16.24	180	180.33	0	0
LOP-100	84	80	0	0	0	0	124	96	11.61	0	26.81	309.53	80	212.7	326.06	1.53	15.75
LRC	34	34	30.85	22.08	60.05	24.77	36	65	15	7.93	234.1	404.74	80	132.8	168.13	0	0
LRC-100	81	76	0	0	0	0	95	78	0	0	234.1	449.45	80	139.07	216.54	0	0
NPHS	31	31	69.35	55.57	90.6	103.79	0	0	55.59	26.39	0	177.16	80	220.39	265.42	0	0
NPHS-100	90	85	0	0	0	0	0	0	101.03	86.14	126.03	289.35	80	202.36	258.22	12.07	16.08
RB	15	15	81.95	70.45	101.69	103.78	48	30	0	0		165.8	80	241	283.99	0	0
RB-100	60.45	63	0	0	0	0	143	94	0	0	228.38	389.94	80	211.96	270.52	10.69	11.1
REF	30	31	66.75	55.21	102.34	105.23	46	30	1.07	0	0	161.12	80	230.24	269.1	0	0
REF-100	84	80	0	0	0	0	124	96	11.61	0	26.81	309.53	80	212.7	326.06	1.53	15.75
SQ	30	30	51.76	51.76	24.59	24.59	18	18	0	0	0	18.97	18.97	211.96	211.81	0	0
SQ-100	74	74	0	0	0	0	36	36	0	0	0	78.58	78.58	209.75	209.75	13.98	13.98

[5] All installed capacities are in MW

Technology (MW) [5]	Bagasse		HFO-lsce		HFO-msce		Hydro-phs		Lithium-battery		PV-distributed	PV-utility		Wind		Waste-ocgt	
SRW	26	26	55.9	55.9	87.66	87.66	12.7	12	16.51	16.51	0	242.05	242.05	166	166	0	0

8.4. Renewable Shares

In examining the energy system with the solar PV utility limited to 80 MW, several observations can be made regarding the energy system. The renewable energy potential comprised a substantial share of the installed capacities even in the cost-optimal scenarios, which have high renewable energy shares above 79%, except for the LOP (46%), HEU (76%) and HBC (68%) scenarios as shown in Figure 8.5 above on page 94.

In examining the energy system with the 80 MW cap removed from solar PV utility, a similar trend was observed for the cost-optimal scenarios. However, slightly higher renewable shares were observed in the following cost-optimal scenarios: HBC (80%), HBCC (82%), HD (84%), LRC (96%), and NPHS (87%) as compared in Table 8.3 below.

Table 8.3. Comparing the renewable shares for the scenarios with and without the 80 MW Cap on Solar PV utility (Own Creation n.d).

Scenario	Cap on solar PV utility (%)	No Cap (%)
EVUC	81	81
HBC	68	80
HBCC	80	82
HD	81	84
HEU	76	76
HSW	87	
LOP	46	46
LRC	93	96
NPHS	83	87
RB	79	82
REF	84	87
SQ	84	84
SRW	86	86

Key point

- High shares of renewable energy are realized even in the cost-optimal scenarios.
- Slightly higher shares of renewable energy are realized in several of the scenarios by including more solar PV at the utility scale.

8.5. Wind resource

As mentioned in Harewood et al. (2021, 121), due to the higher capacity factor of the wind resource, compared to the other renewable resources, large utility scale wind capacities are installed in all scenarios with the solar PV capped at 80 MW. As mentioned above, in all the cost-optimal scenarios, the demand is covered by wind, followed by conventional capacities. The installed wind capacity for the cost-optimal scenarios ranged from LRC (168.13 MW) to HD (369.60 MW), with the noted exception being the SRW (166.00 MW), as there was a cap on the wind resources, as shown in Figure 8.4 and Figure 8.5.

The wind resource has the highest installed capacities for all the 100% RE scenarios except for SRW-100 (168 MW) and LRC-100 (168.13 MW), except for the cost-optimal LRC, HSW and SRW scenarios. This result is expected in the SRW scenario, as the solar resource potential was doubled to 500 MW, whereas the wind resource potential was reduced to 166 MW. Notwithstanding, the maximum wind capacity was installed. When there is a significant reduction in solar PV costs, as in the LRC cost-optimal scenario, as shown in Table 8.1, the wind resource has one of the lowest installed capacities at 166 MW.

As described in Harewood et al. (2021, 124), the REF scenario showed that 58 MW of additional wind resources were required to meet the demand from increased electrification for passenger transport and cruise ships compared to the SQ cost-optimal scenario. No more is this evident than in comparing the installed capacities of the REF cost-optimal scenario to the scenarios with uncontrolled e-mobility demand, such as the HBUC and HEU scenarios, which required 46 MW and 82 MW additional wind resources, respectively. A similar trend is observed in the 100% RE scenarios, but substantially higher installed wind capacities were required.

In examining the energy system with the 80 MW cap on the solar resource removed, the wind dominated the renewable energy shares only in the EVUC (cost-optimal and 100% RE scenario), HEU (cost-optimal and 100% RE scenario), HD (cost-optimal), NPHS (100% RE) and REF (cost-optimal).

In the cases of the EVUC and HEU (cost-optimal scenarios), additional wind resources were required to cover the demand from the uncontrolled charging of passenger transportation. Similarly, in the case of the cost-optimal HD scenario, more additional wind resources were required for the additional demand. In the case of the NPHS 100-RE scenario, installing more solar PV at the utility scale was cheaper, particularly for meeting the charging demand from the controlled charging of passenger transportation and installing higher shares of utility scale wind once the cap was removed. As mentioned above, the NPHS is the same as the REF scenarios except for the exclusion of PHS.

Consequently, removing the 80 MW cap on the solar PV utility only impacts the scenarios with controlled charging, as solar PV utility was the primary renewable resource, followed by wind energy. Although the slight reduction in installed capacities, as shown in Table 8.2 above, the wind resource remained the primary renewable resource in the scenarios with predominately uncontrolled charging of E transportation, such as the HEU cost-optimal and 100 RE scenarios and EVUC-100 scenarios. For the EVUC cost-optimal, the cap had no effect on the installed wind capacity.

Key point

- More wind resources are required to satisfy the demand from the uncontrolled charge of e-mobility, even with the increase in cheaper solar PV at the utility scale.

8.6. Solar resource

With the 80 MW cap on solar PV utility, the maximum possible solar PV-utility potential of 80 MW was used in all the cost-optimal and 100% RE scenarios except the EVUC, HSW, HEU, LOP, SQ and SRW (c.f. Figure 8.4). For the HSW and SRW cost-optimal scenarios, the solar resource potentials were increased to 500 MW; consequently, higher shares of solar PV-utility were installed in HSW (solar PV utility 161.12 MW) and SRW scenarios (solar PV utility 242.05 MW). For the SQ-100 (78 MW), there was no need for the maximum installed solar PV utility as the demand excluded the e-mobility.

In the EV passenger transport, EVUC cost-optimal scenario, no solar PV resources were installed. For the EVUC-100 scenario, only 80 MW of solar PV utility was required as opposed to solar PV distributed due to the higher costs of the installed solar PV distributed compared to the solar PV utility; this was further examined when the 80 MW cap was removed. Notwithstanding, more solar resources were required despite the higher costs for the 100% scenarios with controlled e-mobility charging, such as the HBCC-100 (solar PV utility -101.45 MW and solar PV distributed -80 MW). As shown above, in Figure 8.4 and Table 8.2, this was particularly the case in the HEU scenario as more wind resource was preferred, about 388.8 MW, with more uncontrolled charging of passenger transportation over the addition of more solar PV distributed that was limited to 65.18 MW.

In examining the removal of the 80 MW cap on the solar resource in all scenarios, including the cost-optimal and the 100% RE scenarios, no solar PV distributed was installed due to the lower costs of the solar PV utility. As observed in the scenarios with the 80 MW cap on the solar PV utility, no additional solar resources were installed in the cost-optimal scenarios with uncontrolled E-transportation charging, such as the EVUC and HEU. In general, as shown in Table 8.2, the solar PV-distributed reached the highest installed capacities in the 100% - RE scenarios, as examined in the LRC-100 (449.45 MW), which can be attributed to the reduced costs for installed capacities of solar photovoltaics, mainly the solar PV distributed. Also, additional photovoltaic resources were required despite the installation costs to attain the final 100% RE scenarios due to higher energy demand as observed in the high demand - HD-100 (200 MW) or the reduced biomass potential - RB-100 (228 MW).

Key point

Controlled vs. uncontrolled charging

- Comparing these scenarios to the REF scenario, the results show that higher shares of wind resources were required to cover the uncontrolled charging of passenger transportation as in the EUVC or HEU scenarios. Conversely, in scenarios such as the REF and HBCC dominated by controlled charging of E-transportation, it was cheaper to install higher shares of solar resources in the form of solar PV utility to cover the controlled charging of the passenger transportation. Also, the results highlight the importance of solar PV installation costs on the distributed scale compared to the utility scale. As solar PV costs at the residential scale are twice the price at the utility scale, the model consistently selected solar PV utility over solar PV distributed except when the solar PV utility was capped. With the cap on the solar PV utility, due to the higher capacity factor of wind, the demand is mainly covered by wind, followed by conventional supply in the cost-optimal scenarios. In the LRC scenarios, the PV resource is the second-largest share of electricity. However, when the 80 MW cap on solar PV is removed, solar PV utility has the largest electricity share, followed by wind and conventional dispatch in the scenarios.

8.7. Conventional Dispatch

As noted by Harewood et al.(2021, 124–25), when analyzing the energy system with an 80 MW cap on solar PV utility, it was found that higher conventional capacities were required in the REF scenario (66.75 MW LSCE and 102.34 MW MSCE) compared to the SQ scenario (51.76 MW LSCE and

24.59 MW MSCE) to meet the demand from controlled charging of passenger EVs and cruise ship demand (c.f. Table 8.4). Compared to the REF scenario, due to the absence of transportation demand, there was no need to install high shares of conventional dispatch in the SQ scenario lsce (51.76 MW) and msce (24 MW). Generally, the conventional dispatch for the lsce ranged from 30.85 MW (LRC) to LOP (122.92 MW). In contrast, due to the lower capital cost of the medium-speed diesel compared to the low-speed diesel, higher capacities of medium-speed diesel were installed, ranging from SQ (24.59 MW) to 148.35 MW (LOP) scenarios. As expected with a decrease in oil price, the highest installed capacities of conventional generation were installed lsce (122.92 MW) and msce (148.35 MW). For the LOP scenario, the installed conventional dispatch was exceptionally high compared to the other scenarios, as the oil price was reduced by 50% compared to the reference scenario, resulting in the highest installed capacities of medium and low-speed diesel genets and the lowest installed capacity of renewables in the form of 180 MW of utility wind to service a peak demand of 302.45 MW. In addition, due to high demand in the HD scenario, high shares of conventional dispatch lsce (100.78 MW) and msce (113:12 MW) were required compared to the REF scenario. Also, in the HBC scenario, to compensate for the high biomass cost, it was cheaper to install high shares of conventional dispatch lsce (105.53 MW) and msce (98.35 MW) over more hydro-pump storage or bagasse.

With the removal of the 80 MW cap on the solar PV utility, there was an overall reduction in the capacity of conventional dispatch in the cost-optimal scenarios, except for the LOP, EVUC, HEU, and SQ shown in Table 8.4 below. In the case of the cost-optimal HEU or EVUC scenarios, the uncontrolled EV demand was satisfied by wind and conventional dispatch, and an increase in the solar resources had no impact on the installed conventional dispatch. Similarly, due to the reduced oil price in the LOP scenario, increasing the solar resources had no impact on the installation of conventional dispatch.

Table 8.4. Summarizing the Conventional Dispatch in the scenarios in the Investigation (Own Creation n.d).

	HFO-lsce (MW)		HFO-msce (MW)	
Scenario	**Cap on solar PV utility**	**No-cap**	**Cap on solar PV utility**	**No-cap**
EVUC	78.51	78.51	97.02	97.02
EVUC-100	0	0	0	0
HBC	105.53	73.28	98.35	46.31
HBC-100	0	0	0	0
HBCC	83.2	76.51	106.36	100.09
HBCC-100	0	0	0	124.55
HD	100.78	86.6	113.12	112.64
HD-100	0	0	0	0
HEU	98.95	98.95	85.49	85.49
HEU-100	0	0	0	0

	HFO-lsce (MW)		HFO-msce (MW)	
HSW	55.21	_	105.23	_
HSW-100	0	_	0	_
LOP	122.92	122.9	148.34	148.35
LOP-100	0	0	0	0
LRC	30.85	22.08	60.05	24.77
LRC-100	0	0	0	0
NPHS	69.35	55.57	90.6	103.79
NPHS-100	0	0	0	0
RB	81.95	70.45	101.69	103.78
RB-100	0	0	0	0
REF	66.75	55.21	102.34	105.23
REF-100	0	0	0	0
SQ	51.76	51.76	24.59	24.59
SQ-100	0	0	0	0
SRW	55.9	55.9	87.66	87.66
SRW-100	0	0	0	0

Key point

- Increased cheaper utility solar resources reduce the need for conventional dispatch in all scenarios except for scenarios with significant uncontrolled charging of passenger transportation.

8.8. Bagasse, waste-to-energy and storage

In examining the energy system with the 80 MW cap on the solar PV utility, bagasse resources of around 30 MW were used in all the cost-optimal scenarios, except the reduced biomass - RB (15 MW), low oil price - LOP (0 MW) or high biomass cost - HBC (0 MW) (c.f. Figure 8.4 pg 93 and Table 8.2 pg 95). Overall, this can be attributed to the higher investment costs of bagasse compared to HFO, which has a higher operational cost but lower investment costs as shown in Table 7.5 of Chapter 7. Consequently, bagasse investment was not included in the cost-optimal LOP scenario. Notwithstanding, in all 100% RE scenarios, bagasse resources were used; the bagasse capacity ranged from RB-100 (60 MW) to HD-100 (96 MW) scenarios. In the RB-100 scenario, investment in bagasse is lower as the biomass potential was restricted but balanced with a higher PHS capacity of about 143.69 MW, as shown in Figure 8.4 above on page 93.

In examining the energy system by removing the 80 MW cap on the solar PV utility, a similar trend was observed as above, except that lower installed capacities of bagasse were installed in all the 100% RE scenarios, excluding the SRW-100, RB-100 and HD-100 as shown in Table 8.2 on pages 95. Slightly higher bagasse investments were made to compensate for the reduced wind resource in the

SRW-100 scenario. Similarly, in the HD-100 scenario, more wind energy was installed to cover the increased electricity demand over bagasse.

Using the REF scenario with the 80 MW cap on the solar PV utility was an example; only 1 MW of battery storage was installed. Due to the high costs of the battery capacity, in comparison to PHS, the battery storage was not significantly utilized in cost-optimal scenarios, reaching 15 MW in the LRC scenario and in the scenarios with uncontrolled charging – EVUC (16.90 MW), HEU (16.21 MW) in addition to no pumped hydro-storage scenario - NPHS (56 MW). The battery storage becomes essential in the uncontrolled charging scenarios to meet the shifted charging demand in the evening and when the PV generation cannot compensate for the increased demand from E-mobility.

When there is no PHS (NPHS) in both the cost-optimal and 100% scenarios, significant battery capacity is needed, ranging between 56 MW and 101 MW. However, high PHS capacities ranging between 95 MW to 190 MW were used in all the 100%-RE scenarios. For scenarios with uncontrolled charging, this was especially the case – HEU-100 (190 MW) and EVUC-100 (152 MW) in addition to the scenarios with restricted bagasse RB-100 (144 MW).

Due to the high investment costs, waste-to-energy was used only in the 100%-RE scenarios to balance the energy system without conventional dispatch units ranging from RB-100 (11.10 MW) to HD-100 (17.9 MW). With the addition of even cheaper solar PV utility resources, waste-to-energy was reduced in 100% RE scenarios, excluding the SQ-100, with the most significant reductions in the 100% RE scenarios: REF-100 from 15.75 MW (with the cap) to 1.53 MW (no cap); LOP-100 from 15.75 MW (with the cap) to 1.53 MW (no cap) as shown in Table 8.2.

Similar battery storage capacities were installed when the 80 MW cap on the solar-PV utility was removed except for the NPHS (26.39 MW), LRC (7.93 MW), and HBC (19.71 MW) cost-optimal scenarios. In the case of the NPHS and LRC cost-optimal scenarios, adding more solar PV-utility compensates for the controlled charging of passenger transportation, reducing the need for battery storage. For the HBC-cost-optimal scenario, a higher share of lithium battery storage was cheaper to install than more expensive bagasse resources. For the 100% RE scenarios, even with more solar resources, a higher share of battery storage was still required to compensate for the uncontrolled charging of passenger transportation (c.f. Table 8.2 pg 95).

Key points

- Waste-to-energy is not a primary option in achieving 100% renewable energy scenarios due to its high investment costs compared to bagasse. Cheaper solar PV utility reduces the waste-to-energy in several scenarios, with the most significant occurring in the REF-100 scenario.
- To achieve the 100% renewable energy scenarios, installing more solar PV at the utility scale can reduce the need for storage. However, if the charging of e-mobility is uncontrolled, the system will require more storage resources.

8.9. Operation of the dispatchable generation

The dispatchable generation, PHS and bagasse operation were shown in Figure 8.6 and Figure 8.7 for the REF and HEU cost-optimal and 100% RE scenarios with the 80 MW cap on the solar-PV utility as an example. The PHS was charged in the afternoon due to a high solar PV electricity supply, producing energy at night and early morning. Figure 8.6 below shows that despite increased installed capacity from REF (46 MW) to REF-100 (124 MW), the pattern remains the same throughout the year.

However, the pattern changes for the bagasse, with bagasse operating in full load for most of the year in the cost-optimal REF scenario. However, in the 100% RE scenario, the bagasse operates flexibly as a peaking and backup unit that supplies energy to the system during low RE energy production periods, for example, due to a substantial drop in wind supply between September and October. During this period of low wind energy, bagasse is heavily utilized, which was particularly the case in the 100-REF scenario. Therefore, bagasse was less utilized during the summer when solar PV and wind energy production were high, and there was a reduced demand due to the absence of cruise ships, which is similar to the beginning of the year when the wind resource is at a maximum despite the greater cruise ship demand, as highlighted in Figure 7.1 above.

In examining the heatmaps for HEU scenarios, the patterns remained the same but with larger installed capacities for the bagasse and PHS, as shown in Figure 8.7 below. In examining the heatmaps for HEU cost-optimal and the HEU – 100 RE scenarios, although the bagasse functioned similarly to the REF scenario, there is a change in the use of the PHS, which operated primarily between 15:00 to 19:00 Uhr. Compared to the REF scenarios, larger installed capacities for the bagasse and PHS were also used in the system, as shown in Figure 8.7 below. The operation of the dispatchable units shows the need for a flexible operation to manage prolonged periods of no-production from renewable resources such as wind, which is heavily utilized in the energy system. Also, a similar trend was observed in dispatchable and storage operations after the increase in the solar PV resource at the utility scale, but with slightly lower installed capacities.

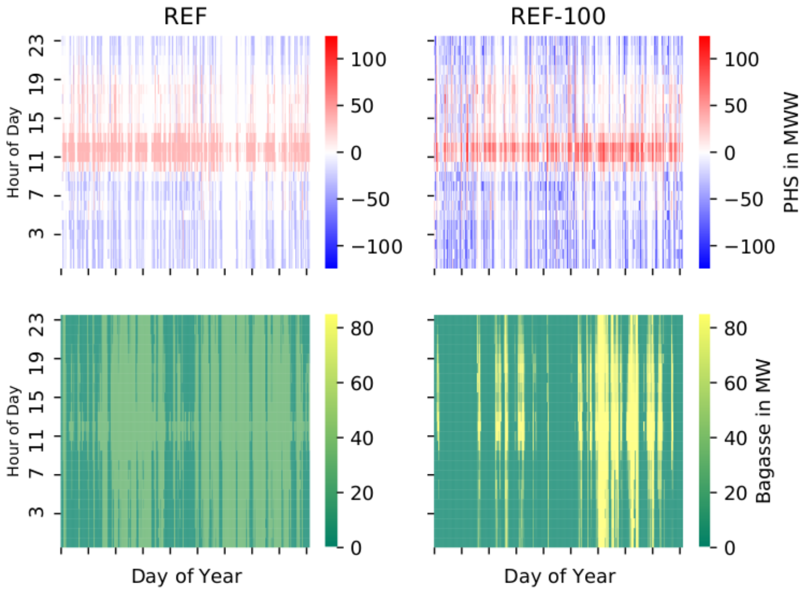

Figure 8.6. Summarizes the operation of the dispatchable generation in the REF-cost-optimal and REF-100 scenarios (Own Creation n.d).

Key points

- The PHS is a versatile generator that can be dispatched as needed to supplement power production from both controlled and uncontrolled charging demand for transportation.
- There is a strong need for highly flexible generation in the energy system, for example, using bagasse to supplement power during low renewable energy generation or as a peaking unit. As mentioned in Chapter 7, the process is powered by a non-flexible steam turbine, which has certain technical limitations to service the residual load.

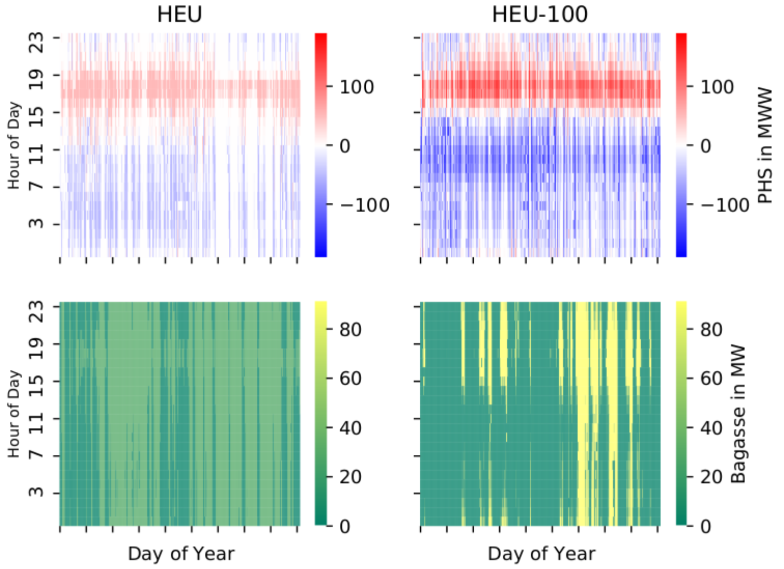

Figure 8.7. Summarizes the operation of the dispatchable generation in high uncontrolled charging of electric buses and passenger transport vehicles scenario (HEU) and 100% (HEU-100) scenario (Own Creation n.d).

8.10. Energy system costs

Considering the unique vulnerabilities of Barbados as a SID state, as mentioned in Chapters 2 and 4. the annualized investment costs per technology for all the scenarios are shown below in Table 8.5. As shown in Harewood et al. (2021, 125), in examining the energy system with the 80 MW cap on the solar PV utility for the cost-optimal scenarios, the total annualized costs range from SQ (126 Mio. BBD) to HD (247 Mio. BBD) and from SQ-100 (192.6 Mio. BBD) to HD-100 (407.16 Mio. BBD) for the 100% RE scenarios as shown in Figure 8.8 and Table 8.5 below. Notwithstanding, the operation costs of the 100% RE scenarios are lower due to the low marginal costs of renewable resources such as wind and solar PV. However, for the 100% RE scenarios, the cost of dispatchable renewables is significantly high, although the share of these resources compared to the wind and solar-PV resources is low. In addition, the model optimized the installation of higher shares of PHS compared to battery power for storage for all the scenarios, except for the no-pump hydro storage (NPHS) scenario, due to the cheaper costs of the PHS. The total annualized costs of energy, which are calculated in the model, selected PHS over battery storage as the battery costs are higher, considering that the battery has a shorter technology lifetime of twelve years compared to the forty years for the PHS. In addition, PHS components such as the reservoir are a one-time cost over the technology's lifetime.

With an increase in solar resources and the removal of the 80 MW cap on the solar PV utility, there were reduced annualized investment costs in most scenarios, especially the 100% RE scenarios, as shown in Table 8.5. The results showed the highest annualized investment cost reductions were in the HBC-100, RB-100 and HD-100 scenarios. As mentioned above, in the case of the HBC-100 and RB-

100, the increased investment in solar resources to cover the reduced power production from the bagasse. In the case of the HD-100 scenario, cheaper solar resources were used to compensate for the increase in electricity demand, which led to reduced energy system costs. However, for the HBC cost-optimal, there was a slight increase in the annualized costs when the cap was removed, as higher shares of solar PV utility were invested, about 115 Mio. BBDS/ annually (c.f. Table 8.6). However, the investment in additional solar PV at the utility scale did not cause an increase in the LCOE.

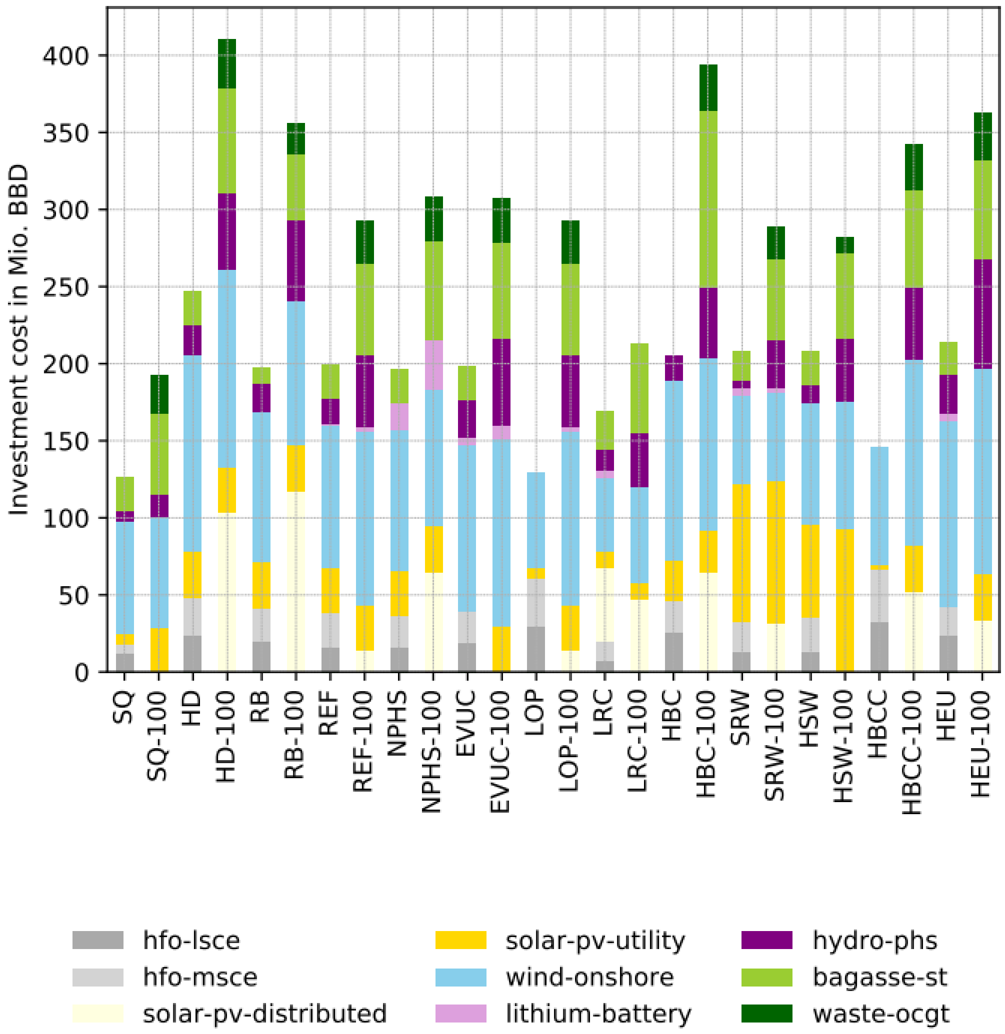

Figure 8.8. Summarizes the investment cost of each scenario with the 80 MW cap on the Solar PV utility (Own Creation n.d).

Table 8.5. Comparing the annualized investment costs in the scenarios (Own Creation n.d).

	Cost (Mio.BBD/year)	
Scenario	**No cap**	**Cap Solar PV utility**

Cost (Mio.BBD/year)		
REF-100	283.2	293.97
REF	208.3	199.28
SQ-100	192.6	192.6
SQ	126.16	126.16
EVUC-100	307.2	307.29
EVCC	183.61	198.97
HEU-100	353.15	362.33
HEU	213.9	213.9
HBCC-100	323.48	341.89
HBCC	225.8	219.43
LRC-100	186.18	212.65
LRC	157.13	169.41
NPHS-100	286.38	307.66
NPHS	208.11	196.69
HD-100	376.04	410.52
HD	258.05	246.89
RB-100	316.46	355.99
RB	206.1	197.27
SRW-100	281.99	288.64
SRW	208.2	208.2
HBC-100	347.55	393.78
HBC	227.93	204.76
LOP-100	283.23	293.11
LOP	129.34	129.34

In examining the system with an 80 MW cap on the solar PV utility, there is no investment in waste-to-energy for the reduced renewable costs in the LRC-100 scenario, whereas, in all the 100% RE scenarios, waste is used by the model, with the highest investment occurring in the HD-100 scenario about 31.73 Mio. BBDS annually as shown in Figure 8.8, and summarized in Table 8.6 below on page 105. Furthermore, with the addition of cheaper solar PV utility, investment in waste-to-energy is reduced with the most significant reductions in the REF-100 and LOP-100 scenarios as mentioned in Section 8.8.

Investment in bagasse is made only in the HBC-100 scenario instead of the cost-optimal scenario due to the high bagasse costs. In the REF-100 scenario, higher investments were made into solar-PV resources to over more expensive bagasse resources in the HBC-100 scenario. A significant reduction in wind resources and dependence mainly on solar resources led to a significantly reduced overall installed renewable energy capacity. Consequently, the cost-optimal SRW and HSW scenarios had lower investment costs for both the cost-optimal and 100% RE scenarios than the REF scenario.

As shown in the HD cost-optimal and the 100% RE scenarios, the demand significantly impacts investment, which requires the highest investment in installed capacities compared to the REF scenarios. Higher investment costs are required with the addition of uncontrolled charging in the transportation sectors, especially for the 100% RE scenarios. For example, the HEU cost-optimal scenario required higher installed capacities of volatile units, particularly utility scale wind and dispatchable units, compared to the REF scenario. In addition, the need for flexible generation is highlighted when comparing the HBC-100 to the REF-100 scenarios; despite the high bagasse costs, investment in bagasse is still required. A similar trend was observed when the cap on solar PV utility was removed; however, the increased solar resource did reduce the scale of investment into the other generation sources (c.f. Table 8.6).

Table 8.6.Summarizes technology costs for all scenarios (Own Creation n.d).

Technology (Mio.BBD[6])/	hfo-lsce		hfo-msce		solar-pv-distributed		solar-pv-utility		wind-onshore		lithium-battery		hydro-phs		bagasse-st		waste-ocgt	
Scenario	No cap	Cap	No cap	Cap	No cap	Cap	No cap	Cap	No cap	Cap	No cap	Cap	No cap	Cap	No cap	Cap	No cap	Cap
REF-100	0	0	0		0	13.8	115	29.75	73	112.03	0	3.66	35.65	46.17	56.7	59.91	2.7	27.8
REF	13.21	15.96	22.65	22.65	0	0	59.91	29.75	79.11	92.46	0	0.34	11.3	17.08	22	21.66	0	0
SQ-100	0	0	0	0	0	0	29.22	29.22	72.7	72.07	0	0	13.6	13.6	52.9	52.9	25.68	24.68
SQ	12.38	12.38	5.29	5.29	0	0	7.05	7.05	72.7	72.7	0	0	6.8	6.81	21.87	21.87	0	0
EVUC-100	0	0	0	0	0	0	34.42	29.75	117.27	120.98	12.47	9.38	53.55	56.48	61.24	62.07	28.29	28.68
EVUC	7.36	18.78	13.86	20.89	0	0	11.44	0	54.32	107.29	15.13	5.32	11.76	24.03	22.87	21.66	0	0
HEU-100	0	0	0	0	0	33.55	63.6	29.75	126.9	133.93	10.03	0	59.6	70.57	62.97	64.39	29.97	30.45
HEU	23.7	23.7	18.41	18.41	0	0	0	0	120.65	120.65	5.11	5.11	25.35	25.35	20.79	20.79	0	0
HBCC-100	0	0	0	0	0	52.23	107.47	29.75	91.3	121.21	0	0	36.5	46.23	61.27	62.8	26.9	29.67
HBCC	18.3	19.9	21.5	22.9	0	0	46.72	29.77	102.09	108.4	0	0	15.4	17.1	21.75	21.38	0	0
NPHS-100	0	0	0	0	0	64.88	107.58	29.75	69.53	88.72	27.1	31.84	0	0	60.83	64.08	21.3	28.39
NPHS	13.29	16.59	22.35	19.51	0	0	65.8	29.75	75.7	91.2	8.32	17.52	0	0	22.54	22.13	0	0
HD-100	0	0	0	0	0	103.37	138.7	29.75	104	127.58	0	0	34.8	50.03	69.1	68.06	29.3	31.73
HD	20.71	24.1	24.25	24.35	0	0	65.47	29.75	111.95	126.99	0	0	13.6	20.27	21.9	21.42	0	0
RB-100	0	0	0	0	0	117.57	144.9	29.75	72.8	92.25	0	0	35.12	53.34	44.6	42.79	18.87	19.6
RB	16.8	19.6	22.34	21.89	0	0	61.65	29.75	83.01	97.58	0	0	11.49	17.83	10.75	10.63	0	0
SRW-100	0	0	0	0	0	31.36	126.4	92.95	57.04	57.04	0	2.63	32.52	31.62	53.07	51.78	13	21.25
SRW	13.37	13.37	18.87	18.87	0	0	90	90	57.04	57.04	5.2	5.2	4.73	4.73	18.99	18.99	0	0
HBC-100	0	0	0	65.12	0	26.53	127.8	112.33	57.73	0	0	0	29.18	44.91	107.9	115.44	24.9	29.45
HBC	17.5	25.2	9.97	21.18	0	0	105.8	26.53	74.62	115.86	6.21	0	13.77	15.59	0	0	0	0
LOP-100	0	0	0	0	0	13.8	115.09	29.75	73.09	112.03	0	3.66	35.65	46.17	56.71	59.91	2.7	27
LOP	29.4	29.4	31.9	31.9	6.04	6.04	61.96	61.96	0	0	0	0	0	0	0	0	0	0
LRC-100	0	0	0	0	0	46.87	64.27	11.44	39.59	61.65	0	0	29.18	35.28	53.14	57.41	0	0
LRC	5.28	7.38	5.33	12.93	0	46.87	57.8	11.44	37.8	47.86	2.5	4.93	24.14	13.64	24.19	24.36	0	0

[6] All costs are in Mio.BBD annually.

For the scenarios with the 80 MW cap on the solar PV utility as an example, the levelized costs of electricity (LCOE) for the scenarios are shown in Figure 8.9 and Table 8.7 below, which support a moderate increase from the cost-optimal to the 100% RE scenarios. The LCOE costs ranged from 0.17 (LRC) to 0.25 in the HEU and HBC scenarios, whereas for the 100% RE scenarios, the costs ranged from 0.18 (LRC) to 0.33 (HBC). In the REF scenario, the LCOE increased slightly from BBD 0.18/kWh to BBD 0.20/kWh. Notwithstanding, the energy system costs were mainly based on generation costs and did not accommodate for grid expansion or grid operator costs.

The LRC scenario shows that over a 90% RE is possible for the cost-optimal scenarios whilst keeping the system costs below 0.20 BBD/kWh. Compared to the REF scenario, the NPHS scenario showed that pump hydropower can lower the costs of 100% RES. Furthermore, as noted by Harewood et al. (2021), the value of the PHS is only slightly impacted by higher renewable energy costs, lower oil prices and reductions in demand. The HBC cost-optimal and 100% RE scenarios show that LCOE increases significantly when the costs of dispatchable renewable-based generation, such as bagasse, are high or reduced. With the removal of the 80 MW cap on the solar PV utility, there is a slight reduction in the LCOE costs of the energy system for the 100 RE scenarios, as shown in Table 8.7 below.

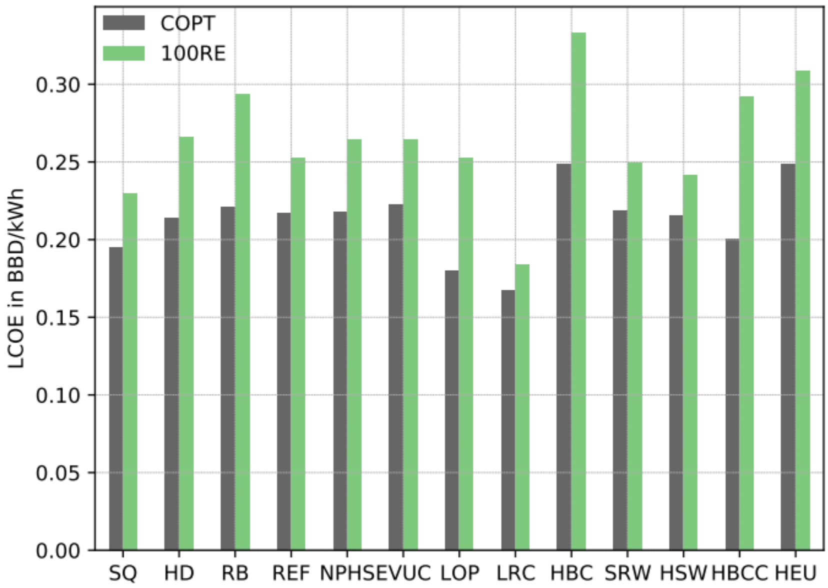

Figure 8.9. Summaries the levelized cost of energy in Barbados currency for every scenario (Own Creation n.d).

Table 8.7. Summarizing LCOE for the scenarios (Own Creation n.d).

LCOE BBD/kWh		
Scenario	No cap	Cap on solar PV utility
REF-100	0.24	0.25
REF	0.22	0.22
SQ-100	0.23	0.23
SQ	0.2	0.2
EVUC-100	0.26	0.26
EVCC	0.22	0.22
HEU-100	0.3	0.31
HEU	0.25	0.25
HBCC-100	0.28	0.29
HBCC	0.24	0.24
LRC-100	0.16	0.18
LRC	0.15	0.17
NPHS-100	0.25	0.26
NPHS	0.22	0.22
HD-100	0.25	0.27
HD	0.21	0.21
RB-100	0.26	0.29
RB	0.22	0.22
SRW-100	0.24	0.25
SRW	0.22	0.22
HBC-100	0.3	0.33
HBC	0.24	0.25
LOP-100	0.24	0.25
LOP	0.18	0.18

Key points

- PHS is selected over battery storage because it has lower annualized costs.
- Demand significantly impacts investment costs in HD scenarios, especially with the addition of uncontrolled transportation charging, as observed in the HEU 100% scenario.
- An increase in solar PV at the utility scale reduces the annualized investment and technology installation costs in most scenarios, with a slight reduction in the LCOE.
- There is only a moderate increase in the LCOE of the energy system cost between the cost-optimal and 100% RE scenarios.
- The cost of the flexible generation significantly impacts the LCOE as shown in the HBC cost-optimal and 100% RE scenarios.

8.11. Model and sensitivity analysis

8.11.1. Analysis of fixed installed solar PV distributed capacities

Sensitivity and other scenario analyses were conducted to test critical points for renewable energy installation and system costs. As recently as 2023, about 100 MW of solar PV distributed will soon be connected to the power grid. Although, the first expansion of renewable energy was at the utility scale, a rapid expansion of solar PV occurred at the distributed level with the implementation of renewable energy tariffs , which includes solar PV systems that are around 200 kW – 1 MW sized systems. The GoB has stated that distributed solar PV may be capped pending further grid expansion and improvement of grid services, focusing on utility scale PV based on system planning.

The assumption in this set of scenarios is that the solar PV distributed reached 100 MW on the power grid, and the subsequent expansion of the solar resource was focused on the utility scale level. Using the REF scenario as an example, two new scenarios were created, REFCU and REFNCU, and investigated. In the REFCU scenarios, while 100 MW of solar PV distributed was already installed, the solar PV utility was capped at 80 MW, in keeping with the investigation by Harewood et al. (2021, 124) and the model optimized the system. In the REFNCU scenarios, there is no cap on the solar PV utility. Thus, the model optimized the energy system with cheaper solar resources, as shown in Table 8.8 below.

Examining the 100% RE scenario, with the cap on the solar PV utility (REFCU), no more solar PV distributed is installed. Instead, the maximum possible capacity of solar PV utility (80 MW) is installed, and more utility scale wind is installed (260.79 MW) (c.f Table 8.8). When the solar PV utility cap is removed, the model can optimize the system with cheaper solar PV utility. No further solar PV distributed is installed. Instead, 209 MW of solar PV utility with 212 MW of utility scale wind are installed. In comparing the REFCU-100 and REFNCU-100 scenarios, with the inclusion of cheaper solar resources, more bagasse was installed to complement the variability of the solar resource; however, the waste-to-energy was significantly reduced to 1.53 MW. In comparing the LCOE of the 100 % RE scenarios to the REF scenario, there was a reduction in LCOE for the REFCU and REFNCU scenarios. However, even with the inclusion of cheaper solar resources in the REFNCU-100 scenario, as shown in Table 8.9, due to the scale on investment in solar PV utility, the LCOE was the same as the REFCU-100 (0.21 BBD /kWh).

Table 8.8. Summarize the effect of 100 MW of Solar-PV distributed preinstalled on installed capacities (Own Creation n.d)

Technology (MW) / Scenario	Bagasse	HFO-lsce	HFO-msce	Hydro-phs	Lithium-battery	PV-distributed	PV-utility	Waste-ocgt	Wind
REF	30.5	66.75	192.3	46	1.07	0	80	0	230.24

Technology (MW) / Scenario	Bagasse	HFO-lsce	HFO-msce	Hydro-phs	Lithium-battery	PV-distributed	PV-utility	Waste-ocgt	Wind
REF-100	84.6	0	0	124.38	11.61	26.8	80	15.75	326.06
REFCU	31	55.2	105	30	0	100	61	0	230
REFCU-100	76.8	0	0	113.8	10.2	100	80	14.48	260.79
REFNCU	31.2	55.2	105.2	30.5	0	100	61.12	0	230.2
REFNCU-100	80.1	0	0	96	0	100	209.5	1.53	212.7

Table 8.9. Summarize the impacts preinstalled Solar PV distributed on the LCOE (Own Creation n.d)

Scenario	COPT BBD /kWh	100 RES BBD /kWh
REF	0.22	0.25
REFCU	0.19	0.21
REFNCU	0.19	0.21

Table 8.10. Summarize the effect of the 100 MW of Solar-PV distributed preinstalled in the energy system on investment costs per technology (Own Creation n.d)

Scenario	Bagasse	HFO-lsce	HFO-msce	Hydro-phs	Lithium-battery	PV-distributed	PV-utility	Wind	Waste-ocgt
REF	22.66	15	22	17.08	0.34	0	29.8	92.46	0
REF-100	59.91	0	0	46.17	3.66	13.8	29.75	112	27.8
REFCU	22.09	13.2	22.65	11.33	0	0	22.73	79.1	0
REFCU-100	54.42	0	0	42.3	3.24	0	29.75	89.6	25.56
REFNCU	22.9	13.2	22.65	11.33	0	0	22.73	79.11	0
REFNCU-100	56.71	0	0	35.6	0	0	77.91	73.09	2.7

8.11.2. Sensitivity analysis on excess power production

The sensitivity analysis was conducted, allowing for varying degrees of excess power production/overproduction. In the investigation, the excess supply of renewable energy power in every time step was limited to 10% of the year's peak demand. This was done because earlier model results exhibited high overproduction, making attaining the final 100% renewable energy system impossible or not applicable to represent real-world energy system operation. An energy system with over 70% overproduction would not represent the ideal real-world operation of renewable energy generation systems. Nonetheless, the scenarios were re-examined with 50%, 70%, and 100% excess power production to examine the impact on energy system costs for the final 100% RES.

The model can simulate overproduction with increased renewable energy power or decreased storage. In this case, the overproduction was simulated by removing the limit to increase more installed renewable energy capacities. However, the results showed no increase in the installed renewable capacities, and as a result, the energy system costs remained unchanged despite varying degrees of overproduction.

These results can be attributed to an error in the code that did not allow the removal of the limit on the excess supply of renewable energy power for every time step. This error, which was not fixed in time for the thesis submission, highlights the need for further investigation and will be addressed in future studies.

8.11.3. Sensitivity analysis on solar PV utility

Sensitivity analysis was also conducted on solar PV at utility scale to determine the critical points at which the model optimized the energy system without installing solar PV at distributed scale, in the HSW scenario. As shown in Table 8.11 below, the maximum installed potentials of the solar PV at the distributed scale and utility scale wind were 500 MW and 472 MW, respectively.

In contrast, the solar PV utility potential was initially 10 MW, which was increased to 100 MW. Ultimately, as the solar PV utility reached an installed capacity of 100 MW in the HSWB-III scenario, no more solar PV distributed was installed, which can be attributed to competition with the utility scale wind (c.f. Table 8.12). Specifically, the CAPEX cost of the utility scale wind is more cost-competitive than utility scale solar PV based on the GoB and IRENA estimates as quoted in the IRENA Roadmap for Barbados (IRENA 2016, 117). Even with an increase in cheaper solar resources, the model optimizes the energy mix with higher shares of utility scale wind. Therefore, in examining the LCOE, there is only a slight increase in the LCOE between the HSW (0.24 BBD/kWh) and the HSCA (0.25 BBD/kWh) 100% RE scenarios, with no impact on the cost-optimal scenarios, as shown in Table 8.13 below. However, as explained in Section 8.10, including cheaper solar resources in the form of solar PV utility reduces annualized investment costs by reducing investment in other renewable energy resources, flexible generation, and storage for the 100 % RE scenarios.

Table 8.11. Summarizes the sensitivity analysis conducted on the solar PV utility (Own Creation n.d).

profile\capacity potential (MW)	HSW	HSWA	HSWB	HSWB-I	HSWB-II	HSWB-III
BB-pv-distributed-profile	500	500	500	500	500	500
BB-pv-utility-profile	360	10	80	85	90	100
BB-wind-onshore-profile-zone-4-2006	472	472	472	472	472	472

Table 8.12. Showing the installed capacities for the 100% RE scenarios (Own Creation n.d).

Scenario	Bagasse (MW)	hfo-lsce (MW)	hfo-msce (MW)	hydro-phs (MW)	lithium-battery (MW)	pv-distributed (MW)	pv-utility (MW)	waste-ocgt (MW)	wind-onshore (MW)
REF	30.59	66.75	102.34	46.03	1.07	26.81	80	15.75	326.10
REF-100	84.62	0	0	124.38	11.61	26.81	80	15.75	326.06
HSWA	30	77.6	98	59.7	9.27	0	10	0	304
HSWA-100	84.62	0	0	124.38	11.61	96.81	10	15.75	326.06
HSWB	30.59	66.75	102.34	46.03	1.07	0	80	0	269.1
HSWB-100	84.62	0	0	124.38	11.61	26.81	80	15.75	326.06
HSWB-I	30.5	65.9	102.62	45.31	0.43	0	85	0	266.4
HSWB-I-100	84.62	0	0	124.38	11.61	21.81	85	15.75	326.06
HSWB-II	30.5	65.9	102.62	44.18	0.17	0	90	0	263.6
HSWB-II-100	84.62			124.38	11.61	16.81	90	15.75	326.06
HSWB-III	30.5	65.9	102.62	42.48	0	0	100	0	260.7
HSWB-III-100	84.62			124.38	11.61	6.81	100	15.75	326.06
HSWC	31.08	56.78	105.6	31.92	0	0	150	0	235.17
HSWC-100	79.66			121.98	7.15	0	150	14.96	286.48

Table 8.13. Summarizes the impacts of the sensitivity analysis on the LCOE (Own Creation n.d).

Scenario	Installed Solar PV Utility (MW)	Cost-Optimal BBD/kWh	100% RE BBD/kWh
REF	80	0.22	0.25
HSW	360	0.22	0.24
HSWA	10	0.22	0.24
HSWB	80	0.22	0.25
HSWB-I	85	0.22	0.25
HSWB-II	90	0.22	0.25
HSWB-III	100	0.22	0.25

8.11.4. Sensitivity analysis on utility scale wind

In examining the SWR scenario, the utility scale wind was reduced to 166 MW, which is in keeping with a policy recommendation by the Energy Division. Based on the competition with the utility scale wind resource and the solar PV at the distributed scale, the scenario was tested by lowering the utility scale to 10 MW in a new scenario labelled SWRI. This scenario represents a possible policy direction to focus on the distributed scale solar PV with a reduced wind resource at the utility scale; the results are shown below in Table 8.14. The highest installed capacity of distributed solar PV is 300 MW.

However, the LCOE increases significantly in comparison to the REF scenario as shown in Table 8.15.

Table 8.14. Summarizes the installed capacities for the SWRI scenario (Own Creation n.d).

Scenario	Bagasse (MW)	hfo-lsce (MW)	hfo-msce (MW)	hydro-phs (MW)	lithium-battery (MW)	pv-distributed (MW)	pv-utility (MW)	waste-ocgt (MW)	wind-onshore (MW)
REF	30.59	66.75	102.34	46	1.07	0	80	0	269
REF-100	84.62			124.38	11.61	26.81	80	15.75	326.06
SRWI	22	90	115.5	5.35	5.75	102.29	10	0	166
SRWI-100	73.14	0	0	85.22	8.34	300.9	10	12	166

Table 8.15. Comparing the LCOE for SRWI to REF scenario (Own Creation n.d).

Scenario	Cost-optimal (BBD/kWh)	100 RE (BBD/kWh)
REF	0.22	0.25
SRWI	0.24	0.28

Based on the results above sensitivity analysis was conducted by examining the effect of installing more wind resources on the costs of the energy system. As shown in Table 8.16 below, the solar PV utility and solar PV distributed resource potentials were fixed at 80 MW and 500 MW respectively, in a new scenario labelled LW.

The utility scale wind was increased from 80 MW to 300 MW through scenarios LWTA to LWTD (c.f. Table 8.16), with the lowest installed wind resource of 80 MW, the distributed solar PV reached a maximum of about 393 MW in the LWTA scenario c.f. Table 8.17 with the LCOE reaches a maximum of 0.26 BBD/kWh and 0.31 BBD/kWh, respectively, for the cost-optimal and 100% RE scenarios. The critical point is above 200 MW of installed utility scale wind, where no further solar PV distributed resources are installed, due to the high costs of distributed solar compared to utility scale wind. Consequently, the LCOE reached a minimum of 0.22 BBD/kWh and 0.25 BBD kWh for the cost-optimal and 100% RE scenarios respectively.

Table 8.16. Summarizes the sensitivity analysis conducted on the utility scale wind (Own Creation n.d).

profile\capacity potential (MW)	LW	LWTA	LWTB	LWTC	LWTD
BB-pv-distributed-profile	500	500	500	500	500
BB-pv-utility-profile	80	80	80	80	80
BB-wind-onshore-profile-zone-4-2006	166	80	200	249	300

Table 8.17. Summarizing the installed capacities in the LW scenarios (Own Creation n.d).

Scenario	Bagasse (MW)	hfo-lsce (MW)	hfo-msce (MW)	hydro-phs (MW)	lithium-battery (MW)	pv-distributed (MW)	pv-utility (MW)	waste-ocgt (MW)	wind-onshore (MW)
REF	30.59	66.75	102.34	46.03	1.07	26.81	80	15.75	326.10
REF-100	84.62	0	0	124.38	11.61	26.81	80	15.75	326.06
LW	22	90	115	5.35	5.57	32.39	80	0	166
LW-100	73	0	0	85.2	8.3	230.91	80	8.52	80
LWTA	19.37	83	108	0	0	110	80	8.52	80
LWTA-100	61.7	0	0	109.58	4.41	393.7	80	9.58	80
LWTB	24.0	86.6	103	27	6.22	0	80	0	210
LWTB-100	73.6	0	0	106.3	4.3	164.56	80	13.23	210
LWTC	28.8	73.7	100.9	43.32	0.86	0	80	0	249
LWTC-100	75	0	0	120	1.84	113.7	80	14.15	249
LWTD	30.59	66.7	102.34	46	1.07	0	80	0	265
LWTD-100	84	0	0	124	11.6	26.8	80	15.75	326.06

Table 8.18. Summarizes the results of the sensitivity analysis conducted on the utility scale wind (Own Creation n.d).

Scenario	Installed Utility scale Wind (MW)	Cost-Optimal (BBD/kWh)	100% RE (BBD/kWh)
REF	325.10	0.22	0.25
LW	166	0.23	0.27
LWTA	80	0.26	0.31
LWTB	210	0.22	0.26
LWTC	249	0.22	0.26
LWTD	300	0.22	0.25
LWTE	350	0.22	0.25

Chapter 9 – Discussion of results

9.1. Electrification of transportation

As discussed by Harewood et al. (2021, 123), the results show that the electrification of the transportation sectors, particularly the uncontrolled charging of passenger transportation and buses, will significantly affect the overall demand and be challenging to manage. In particular, covering uncontrolled charging of passenger transportation will also require higher shares of wind resources and pump hydropower.

The HEU and HBCC scenarios indicate that a considerably larger proportion of wind resources and flexible generation was necessary to meet the increased demand resulting from the unregulated charging of passenger transport EVs and E-bus fleets. Moreover, the LOCE and investment costs considerably increased in the HBCC and HEU scenarios due to the higher proportion of flexible generation and wind resources required. Generally, the controlled charging led to a higher proportion of renewable energy, than the scenarios with uncontrolled charging.

While this study did not explicitly investigate the controlled charging of E-bus fleets with renewable resources such as utility-scale solar PV, it did shed light on their charging patterns. As detailed in Chapter 7, E-buses are charged based on usage, typically between 21:00 to 02:00 hrs. Despite not aligning with solar resources, this off-peak charging helps balance the load by spreading the charging demand over the night and early morning when electricity demand is lower. However, as shown in HBCC-100 scenario, this results in higher shares of wind resources.

The topic lends to a broader discussion on demand-side management and policies to exploit off-peak electricity or time-of-use (TOU) rates to encourage E-mobility charging during these times instead of controlled charging with solar resources, as examined in the investigation. As the results show, uncontrolled charging of passenger transport and E buses required higher installed wind and storage resources, whereas controlled charging significantly benefited from increased solar resources. For the current charging profile of E-buses, comparing the LCOE of the REF-100 scenario to the HBCC-100 scenario with additional high E-bus charging, there was an increase from 0.25 BBD/kWh to 0.29 BBD/kWh. Even with an increase in cheaper solar resources in the form of utility scale solar PV, there was only a slight decrease in LCOE from 0.24 BBD/kWh to 0.28 BBD/kWh. With the combined demand from uncontrolled charging of passenger transportation and E-bus charging, as examined in the HEU-100 scenario, in comparison to the REF-100 scenario, there was an increase from 0.25 BBD/kWh to 0.31 BBD/kWh, with the inclusion of utility scale solar PV there was a slight decrease which ranged from 0.24 BBD/kWh to 0.30 BBD/kWh.

Charging during the off-peak time will be better for grid management but more expensive than controlled charging with solar resources. It is not a question of whether to use one policy over the other but rather when to implement the policies and understand the implications. Ultimately, some applications, such as charging the E-buses, may be more suited to using time-of-use or off-peak electricity rates during periods of low demand. However, syncing electricity demands with solar resources will benefit the Barbadian energy system economically. Consequently, these results highlight the role of policies to manage the demand in the transportation sector and the need for more research on demand side management and time-of-use electricity rates for the future energy system.

Key points

- Using controlled charging for charging of E-mobility is significantly more economical for the Barbadian power systems.
- To meet the demand, uncontrolled charging of E-mobility transport results in higher LCOE due to higher installed capacities of wind and storage.
- The current charging program used by the E-bus fleet is manageable but is more expensive than controlled charging using solar PV utility resources.

9.2. Dispatchable renewables

Both Hohmeyer (2017, 71) and Haynes (2019) noted that the bagasse plants would have to operate at 8,000 hours per year at a full load to produce a LCOE of 0.28 BBD/kWh. The model showed the bagasse operating at full-load hours for several hours during the year in the cost-optimal REF scenario in Figure 8.6. However, as explained above the pattern changed in the 100% RE scenario, where “the bagasse operated as peaking and backup that supplied energy to the system only during low wind and solar PV periods, for example, due to a substantial drop in wind supply between September and October. During this period of low wind energy, bagasse is heavily utilized. Therefore, bagasse was less utilized during the summer when solar PV and wind energy production were high, and there was a reduced demand due to the absence of cruise ships. Another occasion biomass is utilized heavily is at the beginning of the year when the wind resource is maximum despite the greater cruise ship demand.” Ultimately, as the system moves to increase higher shares of variable renewable energy power production in a 100% RE system, the costs of bagasse electricity production would increase as full-load hours can be expected to be reduced by half, at about 4,000 hours per year, the cost of energy can be expected to increase from 0.28 BBD/kWh to 0.56 BBD/kWh to recover the costs of the project (Hohmeyer 2017, 72). Furthermore, the pattern remained the same for all HEU and HD scenarios but with larger installed capacities for the bagasse.

Even so, operating at full-load hours in an environment with high shares of variable renewable energy is questionable as in the cost-optimal scenarios. In Chapter 3, it was stated that in an energy system dominated by renewable energy sources, flexible operation of controllable units is necessary to meet the residual load (Faulstich et al. 2011, 143). Hohmeyer (2017, 267) notes that a high steam turbine would take hours to heat up the major system components to 400 degrees Celsius to begin a cold start of the turbine. The cold start of the boiler would be 2 to 6.5 hours, the cold start of the turbine would be about 90 minutes to the part load operation of 15% - 20% and require an additional 8 hours to reach full load to avoid damaging the turbine for a combined total of 10-12 hours to achieve full load operation. Hohmeyer (2017, 267–68) further stated that solid biomass combustion could be entirely shut down during the season when the residual load is expected to be low. During the rest of the season, the operation could be varied between partial load during high renewable electricity generation times, depending on the boiler and turbine specification. The bagasse plant may be operated in stages leading up to critical levels of renewable energy. However, flexible operation, will require fast start-up times and ramping up rates as shown in the 100% RE scenarios, which is highly questionable.

IRENA (2016, 28) also acknowledges challenges in the direct combustion of solid biomass as such plants lack flexibility in operation. The study further recommended a liquid pathway using bagasse to pyrolysis oil for power generation in internal combustion engines, such as low to medium-speed diesel or a gaseous path from bagasse to syngas for combustion in combined-cycle gas turbines. Regarding bagasse to pyrolysis oil, research shows that bagasse pyrolysis with conventional heating at 450 to 550 degrees Celsius has a liquid yield of over 50 wt% and a maximum yield of 53.3 wt% (Lin and Chen 2015; Gaber H. Saif, Wahid, and Ali 2020). Similarly, Baratieri et al. (2009) show that CCGT plants have better electrical efficiency in experimental research, about 40% for bagasse to syngas conversion. However, much of the research remains experimental, with no successfully operating plants. Therefore, the liquid and gaseous pathways are not a commercial option for Barbados within the current timeline for a transition to a 100% RE system but may be further in the future.

Hohmeyer (2017, 268) also endorsed using syngas of king grass, which was capable of dynamic operation with ramp-up rates from no operation to full operation within less than 15 minutes to service the residual load and king grass was not limited by seasonality and could be grown through the year. In addition, the syngas could be stored for hours or days, further allowing greater flexibility. During the investigation, no additional information was provided on the successful use of king grass for energy production, as the project had yet to reach the full-scale demonstration phase.

Similarly, solid waste combustion incineration technology was selected based on the BL&P (2014, 83). Hohmeyer (2017, 90) noted that the maximum capacity for a plant is limited to 11 MW.

Additionally, such a plant would have similar operational dynamics as biomass combustion. According to BL&P (2014, 92), the candidate plant is a boiler used to power a steam turbine, which would not have the flexibility to service the residual load. Typically, waste-to-energy combustion is a gradual and controlled process. Furthermore, the primary purpose of such a plant is waste treatment by burning as opposed to flexible electricity generation. Rapid ramp-up by increasing feedstock input to the combustion can overload and damage the equipment; sudden changes also cause incomplete combustion of the waste feedstock, causing the release of harmful gaseous emissions.

Although plasma gasification was not examined in this investigation due to time constraints, this is a technology for consideration in future studies. The syngas produced can be stored and used during periods when variable electricity generation may be low and, as such, would be more flexible in operation.

Anaerobic digestion (AD) for biogas production is already a proven and viable technology internationally (Schipfer et al. 2022). The selection of feedstocks that can enhance biogas production with cross-cutting linkages in other critical sectors or industries, such as waste management, is essential for Barbados and other SIDS. Holder et al. (2020) showed that river tamarind can be used in co-digestion with fish offal for efficient biogas production and waste treatment. Considering that the fishing industry alone produces 1000 tonnes of waste in the form of fish offal, which is currently dumped, and considering the issues regarding the flexible operation of the direct combustion of river tamarind, anaerobic digestion may be a better consideration for the GoB.

Thompson et al. (2021) have shown success in laboratory-scale experiments using sargassum seaweed using a hydrothermal pretreatment. However, this research was not available at the time of energy system modelling during this investigation and was not considered in the scenario analysis. The project utilized a 300 kW CHP unit to generate heat used in hydrothermal treatment and electrical power, with the electricity sold to the grid at 22.125 cents/kWh BBD (T. Thompson 2021, 136). The study showed that a full-scale plant would reduce 9000 tonnes of wet Sargassum seaweed yearly. However, the assessment showed that the operation of the biogas plant for the sole purpose of electricity may need to be more economically viable. Instead, revenue should be supplemented from the sale of digestate fertilizer, which would improve the economic feasibility through 100% export to foreign markets or improve local agriculture used domestically. Typically, using storage tanks, gas turbines can be operated between 0% and 100% with a start-up time of under 5 mins, and the ramp-up rate typically depends on the gas storage capacities (Schipfer et al. 2022). Thompson (2021) shows the usefulness of using CHP in combination with AD technologies. CHP units powered by biomass combustion have already been used as flexible operational generators to service the residual load. Lauer et al. (2020, 2–3) found that an increased proportion of biogas plants led to less demand for extra flexibility options and reduced the need for conventional power plants with higher marginal costs and greenhouse gas emissions. In addition, flexibly operated biogas plants benefit the energy system by contributing to stable power grid operation at the distribution grid level, lowering the demand and investments for power grid expansion (Trommler et al. 2017).

The suitability of large biomass projects such as the Cane Industry Restructuring Project compared to smaller flexible generation technologies warrants further consideration for grid and socio-economic implications. Typically, large biomass projects would require large-scale investment and would have little room for broader participation from members of the public, not including the local credit unions or cooperatives as potential investors. However, smaller flexible CHP units powered by biogas in the correct fiscal and policy environment may allow more public members and smaller businesses to participate in the energy sector. Furthermore, the significance of such large projects will require grid expansion as potential sites for large biomass plants are far from major population centres, leading to increased line loading on the current 24 kV transmission and distribution power grid. In comparison to smaller flexible decentralized generation units utilizing biogas or CHP, which would be more manageable on the power grid for utility and better integrated in the energy system.

In Germany, the CHP biogas plants participated in the secondary control reserve and tertiary control power, which were required to supply electricity within 5 and 15 minutes, respectively, which fits in the Barbadian energy system, with PHS or batteries providing a primary control reserve (IRENA 2020b, 8–10). Typically, using storage tanks, gas turbines can be operated between 0% and 100% with a start-up time of under 5 mins, and the ramp-up rate typically depends on the gas storage capacities (Schipfer et al. 2022).

Nonetheless, more research on the extensive implementation of smaller CHP units power by biogas requires more examination, which was not possible during this investigation due to time and funding constraints but is recommended in future studies. This research did not examine the national scale implementation of biogas; instead, the evaluation was based on the techno-economic assessment and laboratory testing of specific AD projects. Although the research is specific to biomethane production from sargassum seaweed, it also suggests biogas production from bagasse. However, more research is required to support the appropriate selection of pretreatment processes and co-digestion substrates, especially supporting commercial-scale development of the resource (Metwally, Abo-bakr, and Ahmed 2023; Janke et al. 2015, 20688–89). Based on challenges regarding the suitability of direct combustion of bagasse, the GoB must commission national studies on collecting national organic waste streams for treatment with AD. Considering the University of the West Indies Cave Hill Campus is already conducting potential biomethane testing, collaboration with GoB in the form of a centre or specific research institute may go further to normalize biogas and make technical services more available to interested stakeholders.

Key points

- Any dispatchable technology selected to support the 100 RE system must be highly flexible. Flexible dispatch that can be ramped up within mins or seconds as opposed to several hours will be crucial for the 100% RE system. Regardless of the technology selected, servicing the residual load cannot be done with large bagasse or waste-to-energy technologies, as mentioned within the current policy documents for Barbados.
- Furthermore, due to the scale of the investment, these larger-scale projects are not as accessible for the broader public to participate in and benefit from.
- However, garnering public participation may be easier for smaller technologies, such as AD, to produce biogas. Furthermore, biogas is an excellent example of a flexible technology that can service the residual load. Biogas technology is a promising technology that should be considered nationally for further evaluation and investigation.
- However, this will require planning regarding selecting and assessing national waste streams for AD treatment and exploiting synergies between waste management and energy production.

9.3. Solar resource and storage

The results showed that including cheaper solar resources in the form of solar PV utility reduces the installed capacity and annualized investment in dispatchable units and onshore wind at the utility-scale. For example, comparing the REF-100 scenario with the cap on solar PV utility and removing the cap, the annualized investment was reduced from 293.97 Mio. BBD/year to 283 MilBBD/year. In particular, the increase in cheaper solar PV utility benefited all scenarios with controlled E-mobility charging. Using the REF-100 scenario as an example, there was a slight decrease in the LCOE from 0.25 BBD/kWh (with the cap on solar PV utility) to 0.24 BBD/kWh (no cap) with an increase in solar PV utility resource scenarios. The marginal reduction in LCOE can be attributed to competition with the utility scale wind due to the similarity between the investment costs of solar PV utility scale and onshore utility scale wind, as mentioned in Section 8.11.3. Without cheaper solar PV at the utility scale, the model optimizes the energy system with higher shares of similarly priced utility scale wind.

However, this point lends to a broader discussion on solar PV at the utility scale versus distributed scale. In Barbados, distributed solar PV can be considered sub-utility scale solar PV, which includes systems below 1 MW but above which, are considered solar PV at the utility scale. Typically, these systems are more centralized and may be closer to population centres. However, some larger systems may be located on agricultural land, which may sometimes be decentralized. Nonetheless, many of these systems will be centralized, thereby reducing expansion of grid transmission infrastructure. More importantly, these systems are essential to attain a 100% RE system by including public participation. As examined in the MSc Programme Energy Economics course, the 100% RE system will require participation by the whole society, inclusive of smaller investors to benefit from energy independence and financial returns (André Harewood 2013, 191). Also, solar PV systems below and closer in capacity to 1 MW represent financially viable investments for smaller investors who cannot participate at the utility scale but are essential stakeholders in the energy transition. More participation in the financial returns from renewable energy and energy independence benefits these groups of individuals. Energy costs represent a significant expense for residential households. Thereby, savings in energy expenditure due to renewable energy investment contribute to higher savings ratios, especially in lower-income households (Ferroukhi et al. 2016, 27–28). Those who are able to participate in renewable energy from the sale of renewable electricity stimulate economic activity. The income multiplier effect benefits the entire economy, adding additional economic activity generated by spending resulting from savings or income generated in renewable energy (NREL 1997, 2–3). The analysis of the SRW and LW scenarios showed that with a focus on residential solar PV as opposed to cheaper solar PV utility or utility scale wind, the LCOE increases significantly, ranging from 0.28 BBD/kWh to 31 BBD/kWh for the 100% RE scenario, in comparison to the 0.25 BBD/kWh in the REF-scenario. Ultimately, a mix of both solar PV at the distributed and utility scales is ideal for Barbados to balance energy system costs and the economic participation of a wider group of stakeholders. For this reason, community energy and energy co-operatives are important for Barbados. As members of these groups, citizens can invest in utility scale renewables as shareholders in the project.

Distributed solar PV is not without challenges as the distributed nature of electricity generation is more dispersed; as such, the intermittency and variability will require more grid management than solar PV utility (Chaudhary and Rizwan 2018, 4–5). For example, AI-powered systems are currently being explored to improve weather forecasting of variable solar PV electricity (Haynes 2023). Although grid management was outside the scope of the investigation, technologies such as grid management systems, smart meters, and smart grid technologies are within the planning phases. Even so, selecting suitable flexible technologies that can be quickly ramped up and down required by the grid operator will be essential. PHS and battery technologies can fulfil the role of voltage regulation and power quality as they respond quickly to changes in grid conditions. Even so, wind turbines are viable technologies in this capacity, as explained in Section 9.4 below. However, it is worth mentioning that PHS is cheaper for the Barbadian power system.

As mentioned in Chapter 7, initial investigations by energy stakeholders and by Stantec (2016) in Hohmeyer (2017, 260) indicated that potential location and suitable geography should not be an issue for Barbados. Based on these communications with energy sector stakeholders, the potential sites for the PHS were selected and explored within the context of the power system analysis in Section 10.2.2.1 as an option for Barbados. Detailed geological and site studies are required to support the advancement of the project. In the absence of detailed information, the PHS was modelled based on European units using cost and operation data from these projects (Andre Harewood, Hilpert, and Dettner 2021, 120; Simon Hilpert and Harewood 2021). However, the costs would need to be validated with a full-scale economic feasibility study within the context of Barbados. Without PHS, lithium-ion batteries are the only other option for the Barbadian energy system at higher costs, as observed comparing the REF-100 scenario; annualized investment costs were 293.97 Mio.BBD/year & LCOE 0.25 BBD/kWh to the NPHS-100 scenario with annualized investment costs of 307 Mio.BBD7/year & LCOE 0.26 BBD/kWh. Notwithstanding, due to higher investment costs, significantly higher investments were made in the PHS in the cost-optimal scenarios over the lithium-ion batteries.

As highlighted in the Electricity Market Study by Hohmeyer (2017, 74–75), the PHS offers several advantages to batteries. PHS systems can be designed to provide system services such as frequency and voltage regulation. Although battery storage can provide an instantaneous response to changes in grid conditions, PHS provides more significant amounts of energy (IRENA 2020b, 6–7). Notwithstanding, more recent advancements in variable-speed turbines have allowed the PHS systems to reach full output when connected to the network in less than 30 seconds. For example, using variable-speed turbines, the Kops II PHS facility in Austria can reach an output of 180 MW in 20 seconds. Similarly, the Dinorwig PHS facility in Wales can reach 1.8 GW in 16 seconds.

PHS can provide storage for several days or weeks, otherwise referred to as long-term storage, which is essential to compensate for the seasonality in the wind resource for Barbados (Pitorac, Vereide, and Lia 2020, 17–18). PHS provides the highest volume of stored energy to power capacity compared to other storage technologies. In comparison, batteries are suited for hourly energy storage to meet peak demand. Ultimately, combining both technologies with the PHS can provide the bulk of the storage. For example, the Kraftwerksgruppe Pfreimd installed a 12.5 MW lithium battery storage system to complement the existing PHS system (137 MW) (IRENA 2020b, 11–12). In addition, PHS is a proven form of low-cost storage, provided optimal site conditions are satisfied. Consequently, the PHS should be considered for Barbados, and more detailed studies commissioned should examine the implementation of the technology and assess the costs of the technology installation specific geography of Barbados. As mentioned in Chapters 7 and 8, the PHS was modelled with ratios based on European facilities, which were more optimized for peaking power than seasonal storage, which was a limitation based on a need for more information for PHS facilities proposed for Barbados and the model structure, as the model needs these ratios to optimize the PHS. Ultimately, PHS facilities for Barbados would have to be optimized for seasonal storage. Therefore, the cost of the PHS may be slightly higher than calculated in this investigation, which does not eliminate PHS as an option for Barbados but rather highlights a need for a more detailed investigation into the technology. More studies in the form of geography and more engineering approaches would provide the information required to model PHS for the Barbadian energy system better. This investigation stimulates discussion amongst shareholders and the GoB regarding possible technologies to support the 100% RE system.

Key points

- Distributed solar PV may have broader economic advantages as the technology enables more participation in the benefits and buy-in of the transition to a 100% RE system. However, it can cause challenges for the grid operator to maintain optimal operating grid conditions.

- Notwithstanding, battery and PHS technologies can be used for voltage and frequency regulation, with PHS being the cheaper technology for Barbados. This investigation highlights the suitability of PHS, which must be supported with engineering studies to provide details to inform policy planning.

- Solar PV at the utility scale will require grid expansion and reduce annualized investment costs, but only with slight reductions in LCOE.

9.4. Wind energy for power and grid stability

Wind energy was shown to be a critical renewable energy resource for Barbados; however, at the time of this investigation, no large-scale wind farms were installed. The island has an excellent wind resource that will form the backbone of the energy system, and pursuing wind energy in the future is a no-regrettable option for Barbados. Concerns about grid stability and reliability of the power supply have been mentioned by energy stakeholders, including the local utility and grid operator (Haynes 2023; Hohmeyer 2017, 9–10). Wind energy is a variable renewable resource, grid operators have mitigated the variability with the resources by using advanced forecasting and real-time monitoring as standard practice to integrate the resource on the power grid. Furthermore, these capabilities are set to improve with the inclusion of artificial intelligence to improve the monitoring of variable renewable electricity (IRENA 2019a, 9). Ultimately, the GoB can work with local grid operators to evaluate and implement these methodologies to achieve 100% RES.

Furthermore, these issues should be included the 100% RE system discussion. In addition, conventional generators have traditionally provided grid stability. However, with more renewable energy replacing conventional generators, wind turbines can provide grid stability. According to Fischer (2020, 5–6), the GirdLoads research project showed that wind turbines using energy stored in their rotors could be used to provide grid inertia. The kinetic energy of wind turbines was shown to be suitable for compensating for the loss of mass inertia and wind turbines can, in the future, provide instantaneous reserves provided wind turbine manufacturers adapt their control modules for this purpose. Andersson (2021, 54–55), using pitch and torque regulation techniques, variable speed wind turbines can be used for frequency regulation and support on the power grid. Since 2012, several European transmission operators have required new wind turbine plants to have active power control capabilities, including emulation of inertial frequency response and power reference tracking (Aho et al. 2012, 3129–30). Further highlighting that the capabilities are proven, the GoB must move beyond seeing wind turbines as just renewable energy generating technologies, including a comprehensive policy on grid stability and providing ancillary services using new non-conventional energy sources. Specifically, the GoB and relevant local shareholders must work on grid standards that specify the performance of wind power plants so that these can contribute to grid stability for the 100% RE system.

The maximum installed wind capacity occurred during HD-100 (371 MW) and HEU-100 (389.80 MW), corresponding to high electricity demand and high demands from uncontrolled charging of the E-bus fleet and passenger transportation. These scenarios represented the worst-case possibilities for demand from electricity and E-mobility. However, as shown in the cost-optimal and REF-100 scenarios, about 269.10 MW and 326.06 MW of installed capacity were required. According to Rogers (2017, 9–10), about 472 MW installed capacity was possible for Barbados. However, to fully utilize the wind resource, planning permission guidelines should be amended to state that wind turbines should be “a minimum of 350m away from any residential dwelling” as opposed to “ wind turbines should be a minimum of 350m from landowners”, which restricts the maximum installed capacity of the wind farm zones used in this investigation. Based on personal conversations with the GoB, the new Integrated Resource Plan 2021, which was not publicly available for analysis at the time of this investigation, the wind resource was further reduced based on amended policies in urban planning and development to 166 MW. However, if GoB intends to pursue a 100% renewable energy system, urban development and planning should be reviewed to exploit the full wind resource potential.

9.4.1. Energy Cooperatives and Communities

Rogers (2017, 16–17) and Hohmeyer (2017, 20–21) recommended community wind in discussing mechanisms for promoting utility-scale wind energy projects. According to Walker and Devine-Wright (2008, 498–99), an ideal community project can be defined as one which is entirely driven and carried through by a group of local people and belongs to the collective benefits of the local community. As examined in the Electricity market study by Hohmeyer (2017, 179–80) and the BNEP (2019, 14–15), a key concern for the GoB and local shareholders is local ownership of the renewable energy sector and the participation of all Barbadians in the energy sector through ownership of renewable energy investments. Furthermore, considering the reduced costs of solar PV at the utility level compared to the distributed level, community energy projects may prove very helpful for ensuring more participation of energy sector stakeholders to share in the financial benefits of renewable energy.

> Community energy projects that include but are not limited to wind may serve to increase the number of non-commercial actors, allow citizens to spend less money on energy, attain a more reliable energy supply, mobilize private capital for renewable energy and improve finances (Kojonsaari and Palm 2021, 5–6). More importantly, even as smaller, more flexible decentralized units in the case of biomass were shown to be critical to the future energy system. In the case of wind energy, energy communities can drive more decentralized systems as the local communities would have the opportunity to establish a link between local energy generation and consumption near the intended community (Hoffman and High-Pippert 2005, 393–94). With more research and modelling on the power grid, managing decentralized generation with adequate grid services may prove more advantageous over a large, centralized

generation removed from population centres, which would require expensive grid expansion and more grid power loss (Bauwens, Gotchev, and Holstenkamp 2016, 136–37).

More importantly, community energy projects encourage public participation in project development and ownership, increasing the odds of success and acceptance of the policy. Considering the challenges in attaining community support for previous wind projects in Lamberts, public participation is critical for gaining social acceptance and support from communities near utility scale wind farms. As mentioned in Chapter 3, most of the renewable energy projects in Barbados, mainly comprised of solar PV, were funded by local investors representing over 100 Mio.BBDS, and in sometimes, lines of credit were given from international banks. However, ownership of renewable resources is primarily local. Therefore, investors in renewable energy can be found in Barbados. Community energy projects may serve to garner the participation of these investors and will also maintain ownership and remain local, with more public participation near the projects. Furthermore, the concept can include all forms of renewable energy technologies, flexible generation units and storage. Considering the benefits of utility scale solar PV as a cheaper renewable energy technology, community energy projects may be used by interested communities to encourage more public participation at lower prices.

As shown in Germany, most community energy projects comprise energy cooperatives. Members/users rather than investors own energy cooperatives. In addition, net earnings are divided pro rata among members not according to their shareholding but the volume of transactions conducted within the firm (Bauwens, Gotchev, and Holstenkamp 2016, 138). In Germany, wind energy comprises 50% of RE deployment, with community ownership estimated to be a 20% share of market ownership. The most common form of community energy project in Germany is a limited partnership with a limited liability company as a general partner. Also noteworthy is that most cooperatives in Germany are active in solar, which yielded higher financial returns than wind.

In Denmark, wind power development is also closely connected to cooperatives formally organized as partnerships where individual citizens invest jointly in procuring wind turbines to operate and sell electricity generated (Bauwens, Gotchev, and Holstenkamp 2016, 139–40). In 2002, cooperatives owned close to 40% of the total 6300 turbines installed, with over 150,000 households owning shares in wind cooperatives. Although the information still needs to be officially updated, cooperatives comprised 15% of all new turbine installations. What was evident during the early 2000s is that garnering local acceptance of wind development would be challenging if only driven by professional developers. Therefore, under the law, developers of new wind turbines were compelled to offer at least 20% ownership to local citizens. It is worth mentioning that community energy projects in Barbados should also include local content or ownership in keeping with one of several key pillars of the BNEP 2019.

9.5. Policy considerations

In the Electricity Market Study, Hohmeyer (2018, 20–21) mentioned several recommendations for successfully attaining a 100% RE system, which are endorsed and recommended by this investigation. In addition, several of these recommendations were used by the national regulatory body (Fair Trading Commission) and the government agency responsible for energy management (Energy Division). However, several critical areas of focus have been highlighted in this investigation:

1 Tariff differentiation by technology, type of fuel (in case of biomass) and resource, quality, project size and location (rooftop and ground-mounted PV).
2 Time of delivery sensitive for dispatchable renewable energy technologies to incentivize operation during the greatest need.
3 Guaranteed 20-year FIT rates to increase investor security through stable Feed-in Tariff payment.
4 Agriculture friendly by including special FIT rates for solid biomass combustion from bagasse and King-Grass gasification other any other flexible biomass fuels sources for power production.

5 Bonus payments for community ownership to encourage broad citizen participation (in community wind parks).
6 Guaranteed priority grid access for renewable energy to increase investor security.
7 Broadest possible eligibility of all relevant RE technologies of all sizes and domestic investors to encourage broad participation in the new energy system.
8 Temporary capacity caps for grid subsections to ensure grid and system stability.

Recommendations 1-4 are specifically financial-based, whereas 5-8 are a combination of technical or explicitly related to community ownership. Regarding financial based points, as mentioned in Chapter 3, the main limitation to successfully deploying renewable energy prior to the Electricity market study by Hohmeyer (2017) was the need for more stable financial support and remuneration for generating renewable electricity. Similarly, as observed by several authors, in Germany and Denmark, the critical support mechanism for renewable energy, including community energy projects, is establishing a stable financial market for renewables through fixed feed-in tariffs (FITs). As in the case of Denmark, other recommendations included but were not limited to guaranteed grid connection and priority of transmission in the case of wind power producers (Bauwens, Gotchev, and Holstenkamp 2016, 140–41). However, considering that in keeping with the recommendations of the Electricity market study, several formal tariff recommendations were formally adopted by the GoB, specifically recommendations 1 & 3, this is an excellent step in the right direction. Tariffs for solar PV in various capacities reaching a maximum of 1 MW, onshore wind ranging from 10 kW to 1 MW, anaerobic digestion and solid biomass reaching a maximum of 1 MW have been approved (FTC 2020, 3). However, to specifically encourage anaerobic digestion for energy production and waste treatment, additional financial incentives that encourage sustainable collection and management of potential waste streams for AD were also recommended (Tesar 2019).

Regarding recommendation 2, the research highlighted the impact of using renewable resources (solar PV) to charge passenger vehicles in a controlled charging scenario. Specifically, it shows the impact of the “time of delivery of renewables” to meet electrical demand, thereby improving system costs and management. Specifically, higher shares of bagasse and wind were heavily used during the evening hours to meet the evening charging of the passenger transportation and bus fleet in the HEU, and high HD scenarios Dispatch must be highly flexible to meet demand in situations where there is a great need. However, the research shows that highly flexible operation of bagasse is required, which is impossible. The research shows that any future dispatchable technology must be highly flexible. For this reason, flexibility requirements and specifications should be included in future policy amendments.

Regarding recommendation 4, the GoB must prioritize flexible generation options instead of large inflexible bioenergy projects such as the direct combustion of bagasse. Based on challenges regarding the scalability of king grass as a candidate for gasification, more flexible operation of biogas is a potential resource that can service the residual load. In 2012, in Germany, an amendment was made to the EEG as a flexibility premium to encourage flexible generation in existing biogas plants. Since 2014, all new biogas plants must generate flexible electricity (Lauer, Leprich, and Thrän 2020, 9) As recommended by Hohmeyer (2017, 177–78), the FIT and remuneration rate should be designed to include providing these services on the power grid. Furthermore, the GoB should mandate that bioenergy technologies in the future energy system be flexible, in addition to the necessary policy initiatives to support the development of flexible bioenergy.

More importantly, the GoB must encourage and incentivize AD to exploit cross-cutting linkages with other sectors, such as AD technologies for electricity generation and organic waste treatment, especially opportunities for co-digestion with other waste streams. Harewood (2021), showed the potential of AD for treating industrial brewery waste. However, commercial viability would improve by co-digesting brewery waste with organic waste streams from other industrial waste-producing businesses. In some cases, waste streams for AD are used for other commercial processes related to the brewery, such as using spent grain as food for cattle farmers that produce dairy production for other companies in the brewery conglomerate. Nonetheless, as a business conglomerate, opportunities for co-digestion of organic waste from sister companies should be considered and supported with laboratory testing. More importantly, this is another example showing the possibility of exploiting waste management and energy production to produce a sustainable solution for Barbados. Before installing a large-scale anaerobic digestion (AD) plant, it is essential to determine the optimal substrates and mixture of substrates for co-digestion. To achieve this, GoB should commission national biomethane potential testing/research and ensure these services are available to energy stakeholders. Conducting biomethane potential testing will inform the selection of suitable waste streams for optimal AD based on the organic waste stream generated domestically. Additionally, optimal biogas plant design should be developed for the AD process. Holder (2020, 4), notes that laboratory testing is required to determine the optimal substrates and substrate mix for co-digestion before a large-scale AD plant is installed. As noted by Holder et al. (2020, 10) and Joseph Tesar (2019), is to ban the dumping of organic waste above a certain threshold from disposal at the landfill and instead use the waste stream for anaerobic digestion. More importantly, a ban on national landfill dumping lends credence to a more detailed national policy on flexible generation, including biogas.

Regarding recommendation 5, a multiplier of 10% was applied to all community energy projects (FTC 2020, 4). Considering the financial strength and broad membership of the local credit union movement, as mentioned by Hohmeyer (2018, 90,162), the involvement of local cooperatives in the energy sector has been encouraged by the Division of Energy, as these groups will be significant stakeholders in the future energy sector (Haynes 2023). The research shows that smaller, flexible, dispatchable renewables such as biogas may be more suitable candidates for the Barbadian energy system. Furthermore, these technologies are more affordable and less complex than large, centralized bagasse projects and may also be more easily implemented in community energy projects.

Regarding points 6 and 8, a fundamental challenge to expanding renewable energy is the difficulty in gaining grid connection, especially for utility scale solar PV projects. These challenges are understandable, as the grid operator has been cautious in granting grid access to maintain a reliable and secure grid. Ultimately, more investigation focusing on grid stability and access is required, and the new Integrated Resource Plan 2021 was completed but, unfortunately, was unavailable for this investigation. However, temporary capacity caps on grid sections may serve to ensure grid stability and improve grid management. Based on the current policy plans for investment into large bagasse energy projects, these projects will require grid expansion as most locations are far from population centres. A detailed expansion plan involves GIS mapping of generation sites concerning demand centres to plan the entire system instead of individual projects. The GoB, from a system perspective, needs to understand where and how much renewable electricity will be produced. The eventual grid expansion and management can be improved by zoning for generations of sites and using capacity caps in weaker grid subsections. Therefore, zones for wind farm development, as discussed in the Electricity market study by Hohmeyer (2017, 180) and Roger (2017, 8) will be important as caps on particular zones can be used to plan grid expansion for the 100% RE system. More research is recommended to support and detail this expansion. Ultimately, this was impossible with the oemof-barbados model, but other tools such as QGIS and PyPSA were used, and some of these issues are examined in the following chapters.

9.6. Limitations of study

Bagasse and waste-to-energy provided flexibility, which significantly impacted the energy system's costs. However, the model examined aggregated supply units as opposed to individual optimized units. Further research on optimal dispatch options is vital. What is clear is that larger gensets of inflexible waste-to-energy and bagasse, compared to smaller gensets of biogas, typically lack the dynamic operation for operating in an energy system with high shares of renewable resources. The model used a green field approach, which neglected existing grid capacities and optimizations in addition to spinning reserves and system dynamics such as ramp-up rates. Ultimately, the Grid Integration Study (2021, 3–4) suggested that 55 MW of solar and wind energy can be taken with the existing system without any mitigation measures, with the integration of 80 MW possible after some mitigation measures. However, these recommendations were made without the consideration of a 100% RE system as a policy target. Although, other studies were commissioned, these were not available for evaluation at the time of this investigation. However, grid interactions and expansion were examined using the 100-Barbados PyPSA model. Harewood et al (2021, 127) mentioned that a perfect-foresight approach was utilized to optimize the energy system for an entire year, which will be difficult to implement. The wind energy installed potentials were installed based in the recommendations of Rogers (Rogers 2017, 9), however, the study was not supported by onsite investigations of the local wind resource. Additionally, more research to support the national implementation of biogas for energy production is required in future investigations.

The PHS was optimized with a storage potential of 5000 MWh, but the input and output flow ratio was fixed at 0.0625. However, this was based on pump storage facilities operated for peak operation instead of optimized for seasonal or long-term storage. Therefore, the reservoir for the PHS may have been smaller than the required operation in the model, which was recognized as a research limitation. However, optimizing the reservoir's correct size is possible with accurate input and output flow ratio data or more detailed information on the turbine design to calculate the ratio based on the proposed investigation of a PHS plant for Barbados.

Hohmeyer (2017, 260) noted that energy sector shareholders had conducted pre-feasibility studies. However, these studies were not available for this investigation and were recognized as a research limitation. However, the modelling was conducted using the available information. More importantly, the modelling framework was created with the availability of more information so that the modelling and results can be updated.

Despite the limitations, the GoB, specifically the Energy Division, can and will be use the model after this investigation to support policy planning. The investigation by Harewood et al. (2021) shows the usefulness of the model. More importantly, the model is open, very flexible and can be expanded to accommodate new technologies or dispatch information. Several recommendations, such as electrifying transportation and cruise ships, must be formally adopted in the Energy Division policy and included in the new IRRP (2021). Considering these investigations will be conducted with commercial ESM, the model will validate report findings and stimulate open dialogue within the energy sector as the model is open source.

9.7. Conclusion

The results support that over 80% renewable energy share is possible in cost-optimal REF scenario with over 90% possible low renewable cost (LRC) scenario. Despite the seasonal variation in the onshore wind, the results show that wind remains the most critical renewable energy resource in the Barbadian energy mix. The investigation further validates the importance of the wind resource as an analysis of the shore-to-ship charging shows that the seasonal variation in the wind coincides with the peak demand for ships. Also, pursuing solar PV reduces energy system investment costs when examining the 100% renewable energy system. However, there was a slight reduction LCOE with the addition of cheaper solar PV resources.

Bagasse and waste-to-energy resources are essential in providing flexible generation, increasing the system costs. However, these technologies are typically incapable of flexible operation to service the residual load, which will become more critical as the shares of renewable energy approach 100%

RES. No more is this evident than with the waste-to-energy, as the primary use of the technology is waste treatment as opposed to flexible operation. Furthermore, with cheaper solar PV resources, waste-to-energy investment is significantly reduced.

Ultimately, flexibility is critical to the operation of the Barbadian energy system. Any dispatch technology must be highly flexible. Therefore, smaller flexible CHP units powered by biogas may be a better option for flexible operation. In addition, based on the policy target of broader citizen participation and the benefit of grid stability from decentralized units near sites of generation, community energy will be essential to support the expansion of renewable electricity to attain a 100% RE system, provided a necessary upgrade of grid management services.

Chapter 10 – Power system analysis tools (PSATS)

10.1. Python for Power System Analysis (PyPSA) Power System Model

The open-source energy system model oemof-barbados was used to examine possible futures of the Barbadian energy system, ranging from several cost-optimal energy systems to the final 100% RES (Harewood, Hilpert, and Dettner 2021). However, as quoted by Harewood et al. (2021, 125), the description of the energy system, including power grid interactions, was not considered within that investigation. Furthermore, the most recent energy modelling conducted on behalf of the GoB at the time of this investigation, which included the IRP Report (2014), the Barbados National Energy Policy as written by GOB (2019) and the IRENA Roadmap for Barbados (2016), also did not consider grid interactions. Therefore, a description of the energy system, which includes grid expansion to accommodate new flows of electricity from generation sources to service the demand in various geographical areas, remained outstanding. Describing the energy system in this detail is essential for understanding the actual costs and technical implications of the 100% RES within the context of the Barbadian energy system. Specifically, other valuable analyses provided by examining the power grid include a more in-depth understanding of the operating conditions of the electrical grid, the calculation of the economic cost solution for electricity generation and a description of other critical grid performance parameters.

More importantly, this investigation represented a pivotal step in progress for policy planning for the Barbadian energy system and the broader group of SIDS. This research was continued from the oemof-barbados model according to the central tenets of open science, which means there is a high degree of transparency. Critical aspects of the data are available to allow other researchers to scrutinize and validate the assumptions and model results. Such progress and understanding of complex power grid and energy challenges can also be discussed to enhance research collaboration. More importantly, to improve policymaking, policymakers can make informed decisions about investment in energy infrastructure based on empirical evidence. The purpose of this investigation is to encourage discussions about the power grid expansion to support Barbados' 100% renewable energy system. It also aims to create the first open-source grid model for Barbados that can be used for energy system planning in other Small Island Developing States. Specifically, to develop a framework and methodology that other researchers can use to model a 100% RES on the Barbadian power grid and in other SIDS in the future.

As mentioned in Chapter 5, the power grid model must be built with a high degree of expandability as the investigation was meant to be resumed after the PhD research was completed to continue supporting policymaking for system planners in Barbados. Moreover, there was a persistent unavailability or inaccessibility of relevant grid information for the investigation. Furthermore, for Barbados and other Small Island Developing States, information availability and accessibility are challenging. Therefore, the model must be expandable to include new sources of available information, such as topology or line data, which can be easily added to the model later. Based on these requirements, the PyPSA power system analysis tool was selected, as described in Chapter 5.

Conducting investigations of the power grid is particularly sensitive considering the ownership of the information, which may be owned exclusively by the power grid operator/utility. Consequently, sharing this information may be considered a competitive advantage over other potential grid operators (Haynes 2019). Furthermore, information on the grid is a high priority for national security, further adding to challenges in securing datasets for the model. Other grid investigations have been conducted for the Barbadian energy system; however, as usual with these studies, little information is usually published regarding the methods used in addition to input and output data.

In Germany, as in other European regions, challenges in data accessibility have been addressed under open data initiatives to make information on power plants, electricity consumption, and grid infrastructure publicly available under open license agreements. These may be available as standardized data sets such as comma-separated values (CSV), JavaScript Object Notation (JSON) or shapefiles (shp). In addition, technical information is made available through secondary data sources such as technical manuals and secondary reports. Notwithstanding, data privacy and security are addressed by anonymizing the most sensitive information, such as some critical infrastructure locations.

Open-source energy system modelling and detailed scenario analysis that included power grid analysis for Barbados is a new undertaking, which means there is no established infrastructure for readily available data sets or initiatives led by the government or private sector to make data available for open-source grid modelling. This lack of data was a critical limitation that hindered the progress of the grid modelling and prevented achieving the initial research goals to examine detailed grid expansion. Information was requested from relevant stakeholders, as summarized in Table 10.1. However, key requested information, such as line costs were unavailable. Despite this, a combination of secondary sources of information, own research, and assumptions were used to create the grid model and develop the framework used in continuing studies. Several solutions were created to address these challenges as summarized in Table 10.1. For instance, topology information for grid infrastructure, such as lines, transformers, or generators, was required for the model but was unavailable. These system components were located through site visits and secondary data sources, including newspaper articles or Google Earth, and loaded as coordinates into QGIS as shape files. The shape files, with information for grid components stored as strings, were directly loaded into the PyPSA-barbados model.

Table 10.1. Detailing the information requested for the model and how that information was utilized(Own Creation n.d)

Component	Information requested from stakeholders	Use of the available information
Loads	1. A description of the loads on the network. 2. Active and reactive power consumption. a. This could be given in very different ways: b. Yearly consumption information. c. Nominal power/assumptions from worst-cases. d. Hourly values from a year.	1. Load information was provided in the form of a sample load profile, which was provided by the Energy Division for creating the oemof-barbados model. 2. Topology information of the loads at the various buses was not available for investigation. Therefore, specific load information for the various buses was estimated based on housing statistics using the Population Census 2010.
Generators	1. The nominal power 2. Start-up costs, less important 3. Shut-down costs, less important 4. Marginal costs 5. Efficiency, relevant to calculate $C0_2$ emissions 6. Topology information such as the longitude/latitude of the generators.	1. The nominal power of the generators was attained from data used in the oemof-barbados model. 2. Specific topology information was not provided as GIS locations. However, the location of generators could be validated from secondary sources of information and Google Earth. 3. Notwithstanding, start-up and shut-down costs were not available.
Lines	1. The type of lines, standard line type 2. The length of the lines. 3. Series reactance and series resistance in Ohm 4. Nominal current, not really, rather: Limit of apparent power in MVA or thermal limit current in Amperes. 5. Topology information available as schematic information which tells you which buses/transformers the lines are connected to: 6. bus0-Information showing the name of first bus/component to which a branch/line is attached. 7. Bus1- Name of second bus to which branch is attached. 8. Capital costs for line types. 9. The global upper limits for the maximum capacity of each extendable line	1. A schematic line diagram of the 24 and 69 kV grids was provided. However, both diagrams needed to be updated since the grid has changed and improved since the schematic was created and provided. As much as possible, this limitation was addressed by updating the information through personal interviews with knowledgeable persons within the government. In particular, more expert opinion was available regarding the 24 kV T&D network

Component	Information requested from stakeholders	Use of the available information
	(s_non_max)	compared to the 69 kV and other proposed higher voltage lines. 2. Based on the schematics provided, the lines were drawn using Google Earth and QGIS and then transferred to the PyPSA model. 3. There was no cost information on the line types to examine grid expansion.
Transformers	1. Transformer type to know the limit of apparent power which can pass through the transformer s_non; the series reactance as base power of the transformer (x) 2. Capital costs 3. Topology information such as the (lon/lat) of the transformer. 0	1. Google Earth and secondary sources of information were used to obtain technical data, and topology information was obtained from Google Earth and QGIS. Other technical information was provided through personal interviews with knowledgeable persons within the government.

10.2. Mapping buses in QGIS

A summary of the main 69 kV and 24 kV transmission and distribution (T&D) network was received from energy sector stakeholders as shown in Figure 10.2 and Figure 10.1 below. As mentioned above, the line schematics were used to confirm how the substations/buses were connected. Some of the information was anonymized to satisfy data security and privacy concern as shown below.

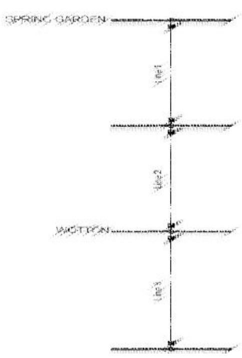

Figure 10.2. Summarizing the 69 kV grid (Own Creation n.d)

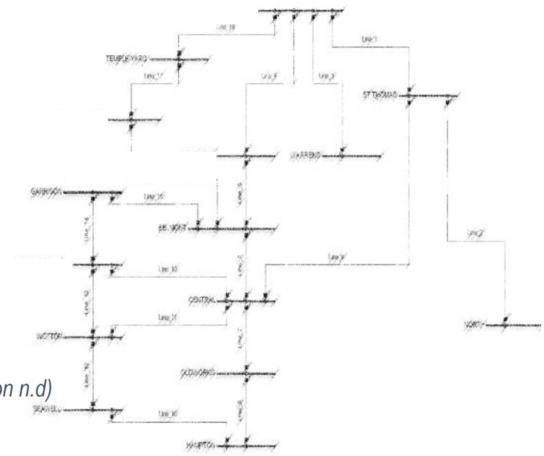

Figure 10.1. Summarizing the 24 kV Transmission and Distribution grid (Own Creation n.d)

As summarized in Table 10.1, in the absence of official information on the grid components, topology information was used to create these line diagrams along with secondary sources of information, site visits and OpenStreet maps and converted shapefiles in QGIS as shown in Figure 10.4 and Figure 10.3 respectively. The green squares represented substations as buses in the 69 kV grid, whereas the red squares represented substations as buses in the 24 kV T&D grid.

Figure 10.4. Summarizing the 69 kV grid as drawn in QGIS (Own Creation n.d)

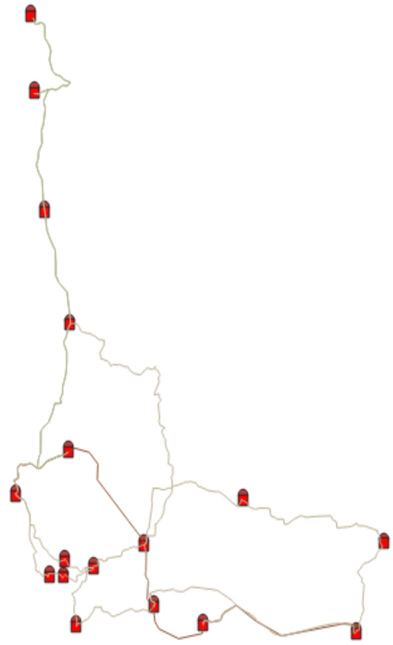

Figure 10.3. Summarizing the 24 kV transmission and distribution grid as drawn in QGIS (Own Creation n.d)

A proposed grid expansion of a 132 kV high voltage line will be installed north of the island, as shown in Figure 9.5 (GE Energy Management 2015; AMEC 2010). However, during modelling, this new line was in the planning phases (Haynes 2019). An example of the proposed line expansion was represented in QGIS as shown in Figure 10.5 below, in which the blue squares represent substations as buses in the network with the 132 kV line running from Trents (TRT) substation in the North of the island to the Watton (WA) substation. As mentioned above, in keeping with the request from stakeholders, where possible, the substations were anonymized, except for a few cases in the report.

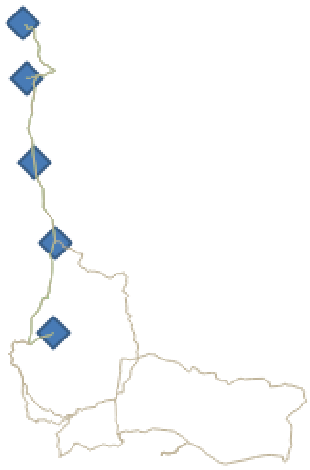

Figure 10.5. Summarizing the proposed 100 kV line expansion in the North of the island (Own Creation n.d)

The 69 kV grid consisted of the four substations shown in Figure 10.4, examined as the present grid, along with the 24 kV grid in the model. However, for a few reasons, the PyPSA-barbados model focused mainly on the 24 kV grid, the backbone of the Barbadian transmission and distribution (T&D) network. Inspection showed that most new generation sources were closer to buses in the 24 kV lines than the 69 kV lines, as shown in Figure 10.8 and Figure 10.9, as explained in Section 10.2.2.2 below.

As mentioned, some of the data on the 24 kV lines needed to be updated, with the addition of newer transformers and lines, which was addressed with expert interviews. In some cases, except for some physical substation locations, no other technical information was available for the investigation. However, compared to the 69 kV grid, the 24 kV T&D grid had a complete dataset except for capital line costs (Haynes 2023; 2019). Nonetheless, a few of the lines in the 69 kV grid, as present, were included in the investigation. However, expansion of the 24 kV to higher line capacities, such as 69 kV or 132 kV, as explained in Section 12.5 of the report, was mainly impossible due to time constraints.

In collaboration with the Energy Division, model source code, shapefiles, and load information collected for the modelling were shared to further discussions on system planning and facilitate negotiations for more information in future studies. However, possible 69 kV and 100 kV lines and substations were included as lines and buses in the model framework and code, so future research could include these, pending the availability of more detailed information. Specifically, the analysis of the present grid can show areas of high line loading and collaborate on which lines are prime candidates for replacement for higher capacities. Furthermore, it contributes to future ongoing discussions on which line capacity may be suitable for the 100% RES.

10.2.1. Mapping of the 24 kV, 69 kV and 100 kV lines.

For the 24 kV grid, each substation in the network was treated as a bus comprised of two types of data: a name and loading. Both are stored as strings with an index number stored as an integer to maintain the data in chronological order in QGIS. Similarly, data was stored for the buses in the other 69 kV and 132 kV networks. The loading refers to the demand at that substation, which is allocated as a percentage based on the population density for each parish, as taken from the latest Population Census 2010. These substations were further grouped into feeders to understand the load distribution, which also reconciled the line diagrams shown in Figure 10.2 and Figure 10.1 to the geographical locations mapped in QGIS as shapefiles shown in Figure 10.4 and Figure 10.3. The bus and feeder geospatial information compiled in QGIS was loaded into PyPSA using a Python script; all the information regarding the location and other data was stored as strings for all the components.

10.2.2. Modelling new sources of generation and storage for the 100% RES

10.2.2.1. Storage

Using the REF-100 scenario as a case study for the grid model, as explained by Hohmeyer (2017, 260–61), several locations were examined as potential sites for a pump hydro storage facility, which was conducted by Stantec (2016) and Stoebich (2016). The height difference required for the upper and lower reservoir was indeed possible for Barbados, which included several possible locations on the plateau in the Scotland district of Barbados. Considering the highest elevation on the island in the Eastern Caribbean is in this area, a height ranging between 240m and 270m is entirely possible for the facility. Similar technical specifications used in the oemof-barbados study were utilized and the installation, based on Hohmeyer (2018, 46) and Homeyer (2017, 260–61), was collaborated by the before-mentioned studies on pump hydro storage for Barbados.

In QGIS, the pump hydro storage facility would have a transformer labelled as Pump Storage, as shown in Figure 10.6 and Figure 10.7. However, the facility would be connected to the grid through either option one at the ST bus, as labelled in Figure 10.6 or option two through substation WA, as shown in Figure 10.7. Nonetheless, as explained above, to highlight the importance of grid expansion and the inadequacy of the current power grid to support the 100% RES, the grid was simulated with connection to the current 24 kV T&D network at bus ST using option one to bus SG at Spring Garden BL&P headquarters.

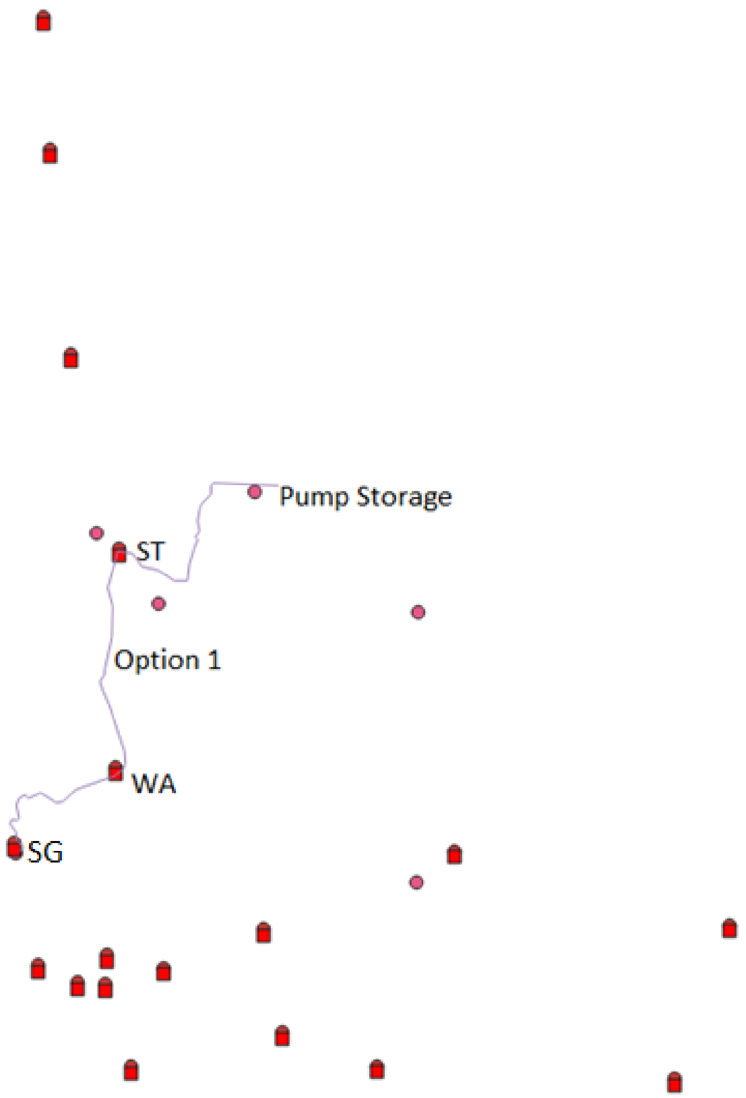

Figure 10.6. Showing the connection of the pump storage to the Spring Garden generation station via the option 1 via ST bus/substation (Own Creation n.d)

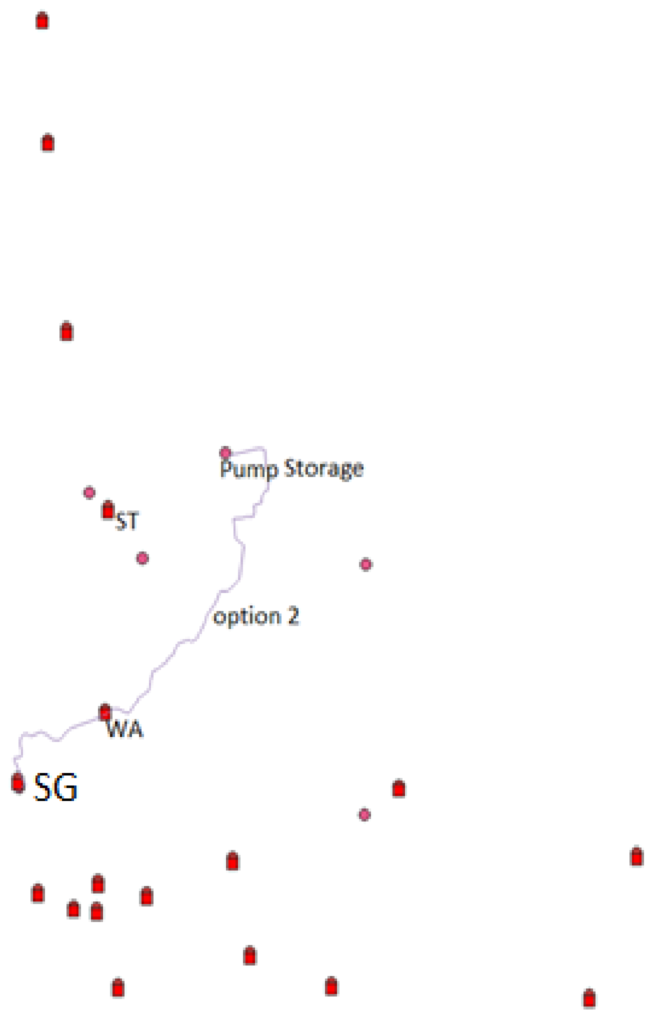

Figure 10.7. Showing the connection of the pump storage to the Spring Garden generation station via option 2 via the WA bus/substation (Own Creation n.d)

The battery storage was located at the SG bus, as this is the headquarters of the BL&P, and interviews with experts within the GoB indicated that this location has an existing strong grid connection and already had smaller-scale battery systems installed to be expanded in the future, as shown in Figure 10.6 and Figure 10.7 above. In the REF scenario of the oemof-barbados model, a pump storage facility with a storage capacity potential of 5000 MWh was used in the scenario analysis, which was optimized to a total installed capacity of 120 MW. In contrast, the battery storage was modelled with a storage capacity potential of 400 MWh, optimized to an installed capacity of 11 MW. However, a specific request by the Energy Division to examine a storage capacity potential of 2900 MWh was considered in system planning.

10.2.2.2. Generation

The sources of generation were modelled from the REF-100 scenario, as summarized in Table 10.2 below. Using information from the latest Population Census 2010, the distributed solar PV was allocated based on the population and number of residential dwellings in each district/parish for 234 MW of installed capacity. The utility scale solar PV was allocated based on proximity to commercial or industrial areas as the solar PV utility resource would be in areas to facilitate EV charging during the day under controlled charging or uncontrolled charging with a total installed capacity of 80 MW. The wind resource was allocated based on the recommendations of Homeyer (2017, 180) and Rogers (2017, 8) into a combination of zones (zones 1 – 7), with the largest installation occurring in the north of the island at substations North (NO), labelled in the diagram, with pink circles representing the 68 MW wind farm and Trents (TRT) substation, with purple circles representing the 66 MW wind farm near the North (NO) substations as shown in Figure 10.8. All other wind farm areas or zones were highlighted as coloured circles, as all other substations remained anonymized. The bagasse was located at both present and unused sugar cane factories, as shown in Figure 10.9. Considering the government's plan for restructuring the sugar industry for energy production from bagasse combustion at one of the three sugar factories, the assumption is that all these locations – Andrews Sugar Factory, Portvale Sugar Factory, Buckeley Sugar Factory would be used for the 100% RES. Consequently, these were located on buses near these former sugar factories such as St Thomas - ST (30 MW) and Old Works - OW (25 MW & 25 MW) respectively c.f Figure 10.9 below. More importantly, as shown in Figure 10.8 and Figure 10.9, based on current policy documents and information, most of the generation is located on/nearer to the 24 kW T&D network as opposed to the present 69 kV grid or any other proposed grid expansion projects.

The nomenclature used in the model referred to renewable energy sources, flexible generation, and storage after the bus where these were situated. For example, in utility-scale solar PV on the CAR bus, the solar PV resource was referred to as CAR-pv-utility or CAR-pv-distributed in the case of solar PV distributed resources. Similarly, utility scale wind resources were referred to as CAR-onshore. The bagasse resources were located on the OW or ST buses and were further differentiated by the name of the generation plant. For example, in the model or results section, the Portland bagasse plant on the ST bus was referred to as ST-bagassePRT or ST-bagasse-Portland. This concept was repeated for bagasse plants at the Andrews (AND) or Buckley(BUK) plantations in addition to the waste to energy at the ST bus, referred to as ST-waste. The storage resources located on SG or ST buses were referred to as ST-phs for pump storage or SG-battery for battery storage.

The buses in the T&D network were referred to by their name and voltage level. For example, the TRT bus in the 24 kV T&D network was referred to as TRT_24_kV, as shown in Table 10.3 below.

Table 10.2. Summary of generation at the buses for renewables and storage technologies. (Own Creation n.d). All units are in MW).

	BB_wind_onshore									BB_pv_utility								bagasse				WtE	Storage	
Bus	zone 1	zone 2	zone 3	zone 4	zone 5	zone 6	zone 7	sum	BB_pv_distributed	solar farm 1	solar farm 2	solar farm 3	solar farm 4	solar farm 5	solar farm 6	present_solar_farm	sum	Bagasse-PRT	Bagasse-BUK	Bagasse-AND	sum	waste-energy	battery storage	pump storage MWh
TRT_24_kV	68								2.88							10	10							
NO_24_kV		66		23					3.33							10	10							
CAR_24_kV			49	22					9.92								0							
ST_24_kV									6.15								0	30			30	27		2900
WA_24_kV									2.90								0							
WP_24_kV									2.90								0							
SG_24_kV									2.90								0						11	
GAR_24_kV									2.90								0							
B_24_kV									2.90								0							
MS_24_kV									2.90								0							
TY_24_kV									2.90								0							
CEN_24_kV									2.90				10				10							
RP_24_kV									5.70								0							
WO_24_kV									5.70						16.81		16.81							
SW_24_kV									5.70								0							
OW_24_kV					15.06		20		8.47								0		25	25	50			
HAM_24_kV					16	47			9.04	15							15							
Total	68	66	49	45	31.0	47	20	326.0	80.12	15	0	0	10	0	16.81	20	61.81	30			80	27	11	

	BB_wind _onshore									BB_pv _utilti y							bag asse			WtE	Stor age			
					6			6																

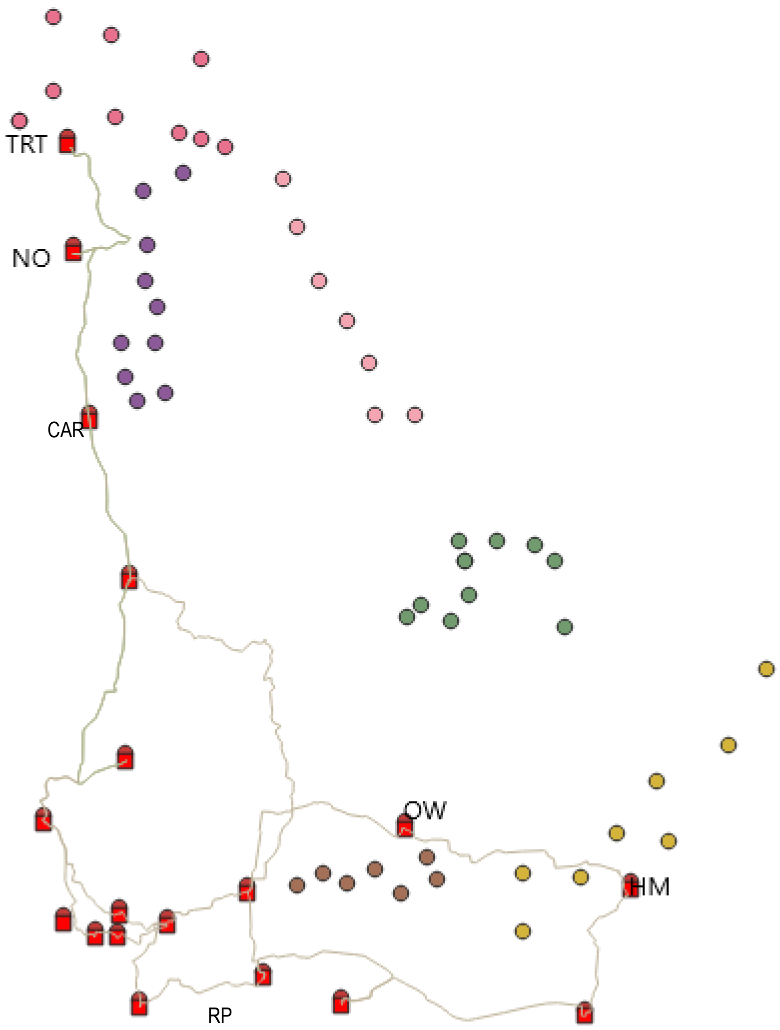

Figure 10.8. Summarizing the Wind Resource allocated into zones (Own Creation n.d)

Figure 10.9. Summarizes the allocation of dispatchable generation and storage in the power system (Own Creation n.d)

10.3. Line capacity

Considering that most of the new sources of generation and storage are located on the 24 kV grid, much of the present grid will undoubtedly require grid expansion as the existing power lines will not support the new energy system. The theoretical capacity of the AC transmission lines can be calculated as shown in Equation 10.1 $P = E_s E_r sin\delta/(L \cdot x)$ (University of Iowa 2024) below. Based on Equation 10.1 $P = E_s E_r sin\delta/(L \cdot x)$ (University of Iowa 2024) , the theoretical maximum capacity of the transmission lines was calculated as shown below in Table 10.3. The theoretical maximum capacity/loading of the AC overhead lines was compared to the line loading calculated in the power grid model in Chapter 12.

Equation 10.1 $P = E_s E_r sin\delta/(L \cdot x)$ (University of Iowa 2024) Where:
$P = Power\ capacity\ of\ the\ transmission\ line\ in\ MW,$

$$E_s, E_r \text{ are the voltages at the sending} - \text{end and recieving end, repectively in kV line} - \text{line},$$

$$\delta = \text{phase difference between } E_s \text{ and the } E_r,$$

$$x = \text{positive sequence reactance per phase in ohm/km}$$

$$\text{and } L = \text{line lenght in km}$$

Table 10.3. Maximum capacity of the AC overhead lines in MW (University of Iowa 2024).

Distance (km)	11 kV	24 kV	69 kV	110 kV	220 kV	380 kV
10	18.5	88	728	1850	7401	22080
20	9.3	44	364	925	3700	11040
30	6.2	29	243	617	2467	7360
40	4.6	22	182	463	1850	5520
50	3.7	18	146	370	1480	4416
60	3.1	15	121	308	1233	3680
70	2.6	13	104	264	1057	3154
80	2.3	11	91	231	925	2760
90	2.1	10	81	206	822	2453
100	1.9	9	73	185	740	2208

In addition to the theoretical maximum line capacity, the distances of the lines as modelled in QGIS are also shown in below in Table 10.4. Table 10.4, shows that the longest line in Barbados is 15 km and most of lines are less than 10 km.

Table 10.4. Summarizes the line lengths as measured in QGIS (Own Creation n.d).

Lines	Length /km
line_17	0.91311
line_6	2.994493
line_7	6.900041
line_4	3.928713
line_5	1.770078
line_16	1.915918
line_18	4.235383
line_1	8.528311
line_3	3.787369
line_14	4.371421
line_12	6.549023
line_10	7.768178
line_13	2.753956
line_19	4.924158
line_9	14.28804
line_15	3.147802
line_8	7.161569
line_20	4.603591
line_21	4.705206
line_22	5.603993

Lines	Length /km
line_26	5.741249
line_24	9.2371
line_25	8.209497

10.4. Structure of the PyPSA model

10.4.1. Lines, transformers, and shunt reactors

Lines and transformers connect buses of the same impedance and nominal voltage level (Brown, Hörsch, and Schlachtberger 2018, 2). Power flows through the lines and transformers based on the power imbalances at the buses within the network. The reactance and resistance of the lines are given per unit values, which depend on the length and the type of line. The line type also determines the rated power capacity the line can carry. Lines and transformers act as "passive branches" as opposed to "controllable link branches". Lines were also modelled with the PI model. The series impedance is given by $z = r + jx$ and the shunt admittance is given by $y = g + jb$ (PyPSA Developers 2021).

Transformers utilize the same parameters assigned to the lines, but the transformers can connect to buses of different nominal voltage magnitudes. However, the resistance and reactance are calculated differently from the lines. For the calculation, several transformer parameters were used, such as load loss, rated capacity, positive sequence impedance, and the short-circuit impedance based on the rating of the transformer. The transformers were modelled with the T model, which was converted to PI model using standard delta-wye transformation (Brown, Hörsch, and Schlachtberger 2017b). For convenience, model users do not have to input the impedances of standard lines and transformer types. For example, in a 50 Hz network, the impedances of both lines and transformer types, as well as other typical parameters, are provided in Python libraries incorporated into PyPSA.

10.4.2. Generators and the flow of energy

A generator can be represented as a bus - that is added for the fuel source and a store to represent the amount of fuel available (Brown, Hörsch, and Schlachtberger 2017b, 2–3). As a partial equilibrium model, PyPSA can examine a more dynamic operation of parameters such as generator ramping up rates, which were not considered in the oemof-barbados model (Brown, Hörsch, and Schlachtberger 2018, 5). However, in the oemof framework, these functionalities can be added to the pre-existing oemof-barbados code. Notwithstanding, this information was not available at the time of modelling. Although it was not examined, this can be included in the modelling framework for future studies.

The generator is then connected to the electricity bus with a link to represent the energy conversion loss. Energy enters the model via generators, storage units or stores with higher energy levels before than after the simulation and any other components with efficiencies greater than 1 such as heat pumps. Energy leaves the model in loads, as storage or stores with higher energy levels after than before the simulation and in lines, links as well as storage units with efficiency less than 1.

10.4.3. Loads

The load component is the maximum demand for the active and reactive power for each hour of the year. The hourly load profile used in the model was created using a sample hourly load profile from 2014, as described in Harewood et al. (2021). In QGIS, the feeders were mapped using the Population Census 2010 and the load at each feeder was calculated using the maximum power demand at the feeder, the power factor ratio, and the simulated hourly load profile. The loads were placed on the feeders in the present T&D network. Multiple feeders can be connected to each high-voltage transformer. The shore-to-ship charging of the cruise ships was located as a load profile at the SG bus, where the E-bus was charged at the NO, ST and WP buses for the Speightstown, Mangrove and Weymouth bus depots. The charging profile of the electric vehicles was also based on the census, as the charging demand was placed on substations based on the population.

The sum of the maximum apparent power demand $(S_{b,f})$ of each bus (b) that connects to the feeders is shown in Equation 10.2, which shows all the feeders and the classification to the buses (PyPSA Developers 2021). The annual load profile was used to calculate the load variation of each load on the buses. The load profile factor (c_t) for each hourly interval (t) is given in per unit value of the maximum load. The equations used to calculate the active power $(\mathrm{p}_{\mathrm{b,t}})$ and the reactive power $(\mathrm{q}_{\mathrm{b,t}})$ for each hourly interval for each bus (b) are shown in Equation 10.3 and Equation 10.12, where $\curlywedge$ is the power factor, which was taken to be 0.85 lagging (Fleischer 2017, 34–35) The demand inclusive of both active and reactive power is calculated for each buses the T&D network was summarized as in Table 10.5.

Equation 10.2[7] $$p_{b,t} = \sum_f S_{b,f} \times c_t \times \curlywedge$$

Equation 10.3 $$q_{b,t} = \sum_f S_{b,f} \times c_t \times (1 - \curlywedge)$$

Table 10.5. Showing the classification to the buses at the 24 kV T&D grid (Own Creation n.d)

Buses with loads in T&D network	Parish	Power demand (MVA)
TRT	St. Lucy	5.258
NO	St. Peter	6.088
CAR	St. James	15.356
ST	St. Thomas	7.678
WA	St. Michael	47.701
WP	St. Michael	_

[7] Equations 10.2 – 10.3 were sourced from Fleischer (2017, 34–35)

Buses with loads in T&D network	Parish	Power demand (MVA)
SG	St. Michael	_
GAR	St Michael	_
BEL	St. Michael	_
MS	St. Michael	_
TY	St. Michael	_
CEN	St. Michael	_
RP	Christ Church	29.278
WO	Christ Church	_
SW	Christ Church	_
OW	St. George	10.651
HAM	St. Phillip	16.522

10.5. Optimal power flow

PyPSA is a partial equilibrium model that optimizes both the short-term operation and long-term investments in the energy system as a linear problem that is solved using linear power flow equations (Brown, Hörsch, and Schlachtberger 2017a, 4). The optimal power flow is conducted in a PyPSA module as an objective function that optimises total system costs, including the variable and fixed operational costs of generation and storage technologies within the physical constraints of the power grid using several variables mentioned in Table 10.6 below (PyPSA Developers 2021, 123). The equations that used these variables to perform the optimal power flow are further expanded in Section 10.6 below.

The energy system is optimized for one year of operation at an hourly resolution based on installed capacitates and transformer information as stipulated in the scenario investigated. In comparison to the non-linear power flow, which is conducted either on a snapshot or a selection of snapshots at once to determine steady-state operating conditions such as voltage magnitude and power flows. Consequently, the non-linear power flow would be used to identify the lines and transformers that must be increased in rated power.

Table 10.6. Summarizes several variables used to describe the energy system (PyPSA Developers 2021)

Variable	**Units**	**Summary of notation**
$\boldsymbol{n, m \in N = 0, \ldots \lvert N \rvert - 1}$		Labels for the buses
$\boldsymbol{t \in T = 0, \ldots \lvert T \rvert - 1}$		Labels for the snapshots or time-points
$\boldsymbol{l \in L = 0, \ldots \lvert L \rvert - 1}$		Label for the branches
$\boldsymbol{s \in S = 0, \ldots \lvert S \rvert - 1}$		Label for different storage types (e.g., battery, hydrogen, etc.) at each bus
$\boldsymbol{r}$		Generator energy carrier label (e.g., wind, solar, gas, etc)
$\boldsymbol{e_{r/s}}$	tCO_2eq $/ MWh_{th}	CO_2-equivalent emissions of energy carrier *r* or *s*
$\boldsymbol{w_t}$	h	Weighting of time t in the objective function
$\boldsymbol{g_{n,r,t}}$	MW	Dispatch of generator at bus n with carrier r at time t
$\boldsymbol{\bar{g}_{n,r,t}}$	MW/MW	Availability of generator at bus n with carrier r at time t per

Variable	**Units**	**Summary of notation**
		unit of nominal power
$\boldsymbol{G_{n,r}}$	MW	Power capacity of generator r at bus n
$\boldsymbol{u_{n,s,t}}$		on/off binary status variable for generator with unit commitment at bus n, at time t
$\boldsymbol{c_{n,r}}$	\$BBDs/MW	Fixed capital cost of extending a generator nominal power by one MW with an energy carrier r
$\boldsymbol{o_{n,r}}$	\$BBDs/MWh	Marginal cost of dispatch generator at bus n for one MWh
$\boldsymbol{suc_{n,s,t}}$	\$BBDs	Start-up cost if generator with unit commitment is started at time t
$\boldsymbol{sdc_{n,s,t}}$	\$BBDs	Shut-down cost if generator with unit commitment is shut down at time t
$\boldsymbol{h_{n,s,t}}$	MW	Dispatch of storage at the bus n with carrier s at time t
$\boldsymbol{\bar{h}_{n,s}}$	MW	Nominal power of storage s at bus n
$\boldsymbol{H_{n,s}}$	MW	Power capacity of storage s at bus n
$\boldsymbol{soc_{n,s,t}}$	MW/h	storage s state of charge (energy level) at bus n at time t
$\boldsymbol{\bar{e}_{n,s}}$	MWh	Nominal energy of store s at bus n
$\boldsymbol{E_{n,s}}$	MWh	Storage energy capacity
$\boldsymbol{c_{n,s}}$	\$BBDs/MWh	Cost of storage s power capacity at bus n
$\boldsymbol{\hat{c}_{n,s}}$	\$BBDs/MWh	Cost of energy capacity storage
$\boldsymbol{f_{l,t}}$	MW	Flow of power in branch l at time t
$\boldsymbol{F_{l}}$	MW	Capacity of branch l
$\boldsymbol{c_{l}}$	\$BBDs/MW	Capital cost of branch l
$\boldsymbol{\eta_{n,r}}$	MW_{el}/MW_{th}	Efficiency of generator r at bus n

10.6. Optimization and objective function

The equations used to conduct the optimization and the optimal power flow using the variables listed above in Table 10.6 are explained in this section. In addition, the equations were used as defined in the PyPSA documentation (Brown, Hörsch, and Schlachtberger 2018, 5). The optimal power flow begins with the optimization of the dispatch based on the objective function composed of the following equations as shown Equation 10.4: branch capacities F_l for each branch; the annuitized fixed costs per capacity c_l; the generator capacities $G_{n,r}$ at each bus n for a technology r; the annuitized fixed costs per capacity $c_{n,r}$. to the dispatch $g_{n,r,t}$ of the units at a time t; the associated variable costs $o_{n,r}$; the start-up and shut down costs when unit commitment is activated $suc_{n,s,t}$ and $sdc_{n,s,t}$ respectively. Furthermore, optimization is done over multiple time periods t representing different weather and demand conditions and each period has a weighting w_t. The investment costs of both the generation and storage technologies are annuitized for the total time $\sum w_t$, which is usually a year. Regarding the optimisation of storage, the equation also includes the power capacities of the storage unit $H_{n,s}$ and the fixed associate costs $c_{n,s}$ of these units, the time-dependent availabilities $\hat{c}_{n,s}$, the energy capacities $E_{n,s}$, associated variable costs $o_{n,s}$ and the positive part of the storage technology dispatch $\left[h_{n,s,t}\right]^+$.

Equation 10.4[8]

$$\min_{\substack{F_\ell, G_{n,r}, H_{n,s}, E_{n,s} \\ f_{\ell,t}, g_{n,r,t}, h_{n,s,t}, suc_{n,r,t}, sdc_{n,r,t}}} \Big[\sum_\ell c_\ell \cdot F_\ell + \sum_{n,r} c_{n,r} \cdot G_{n,r} + \sum_{n,r,t} \left(w_t \cdot o_{n,r} \cdot g_{n,r,t} + suc_{n,r,t} + sdc_{n,r,t}\right) + \sum_{n,s} c_{n,s} \cdot H_{n,s} + \sum_{n,s} \hat{c}_{n,s} \cdot E_{n,s} + \sum_{n,r,t} w_t \cdot o_{n,s} \cdot \left[h_{n,s,t}\right]^+\Big]$$

10.7. Constraints

The power production from the renewable generators is dependent on the availability of the renewable resources at that instance, which varies for every time interval. However, for conventional generation, the power output is constrained based on the per unit value of the nominal installed capacity of the generator, as seen in Equation 10.5 (Brown, Hörsch, and Schlachtberger 2018, 6). Specifically, the dispatch of generators $g_{n,r,t}$ is constrained by the capacity of generation $G_{n,r}$ and the time-dependent availabilities $\tilde{g}_{n,r,t}$ and $\overline{g}_{n,r,t}$, which was given per unit of the capacities $G_{n,r}$. For the conventional generation, the availabilities are usually constant which would be defined as $\tilde{g}_{n,r,t} = 0$ and $\overline{g}_{n,r,t} =$

[8] All of the equation are taken from the PyPSA documentation (PyPSA Developers 2021; Brown, Tom, Hörsch, Jonas, and Schlachtberger, David 2020)

1. For a renewable generator such as wind and solar $\overline{g}_{n,r,t}$, represents the weather dependent availability, while curtailment is introduced as a lower bound on the dispatch $\tilde{g}_{n,r,t}$ (Brown, Hörsch, and Schlachtberger 2018, 6)

Equation 10.5 $$\tilde{g}_{n,r,t} \cdot G_{n,r} \leq g_{n,r,t} \leq \overline{g}_{n,r,t} \cdot G_{n,r} \qquad \forall n, r, t$$

For this investigation, the installed capacity of the renewables was limited to the resources in each bus on the power gird as shown in Equation 10.6 (PyPSA Developers 2021).

Equation 10.6 $$\overline{g}_{n,r,t} \leq \hat{g}_{n,r,t} \qquad \forall n, r, t$$

10.8. Biomass and storage

Biomass and waste-to-energy were modelled as a renewable resource with an annual dispatch limit and were simulated as a storage unit with an initial storage capacity but without a charge capacity; thereby, flexible generators were modelled to fluctuate through the day as optimized in the model. Consequently, flexible operation parameters such as ramp-up rates were not considered during the investigation. The storage nominal power and dispatch were optimised for each snapshot. Each storage unit has three-time dependent variables being $h_{n,s,t}$, $soc_{n,s,t}$ *and* $f_{n,s,t}$ (Fleischer 2017, 26). The discharge of power from a storage unit is constrained by the initial energy storage available. Equation 10.7 represents the dispatch of storage units $h_{n,s,t}$ whose energy carriers are labelled by s whereas, Equation 10.8 represents the storage uptake as the state of charge increases, and Equation 10.9 represents the state of charge of the storage as the capacity currently available as a function of the rated capacity for a storage unit.

Equation 10.7 $$0 \leq h_{n,s,t} \leq \bar{h}_{n,s} \qquad \forall n, r, t$$

$h_{n,s,t}$: Dispatch of storage at the bus n with carrier s at time t

$\bar{h}_{n,s}$: Nominal power of storage s at bus n

Equation 10.8 $$0 \leq f_{n,s,t} \leq \bar{h}_{n,s}$$

$f_{n,s,t}$: The storage uptake

Equation 10.9 $$0 \leq h_{n,s,t} \leq soc_{n,s,t}$$

$soc_{n,s,t}$: storage s state of charge (energy level) at bus n at time t

In optimising the maximum state of charge and the maximum power output independently, the *store* and *link* components were utilised (Brown, Hörsch, and Schlachtberger 2018, 6). The store component is a more basic version of the storage unit (Brown, Hörsch, and Schlachtberger 2018, 6). Specifically, it functions as a storage object with no restraints on charging or discharge. Thus, the charging and discharge power cannot be limited and there is no charging and discharging efficiencies. The energy levels of the store are restricted based on a time series $\tilde{e}_{n,s}$ and the initial energy $e_{n,s,t}$, given the store nominal energy $\bar{e}_{n,s}$. The store has two time-dependent variables nominal energy $\bar{e}_{n,s}$ and the dispatch $h_{n,s,t}$ that are optimised for each snapshot as shown in Equation 10.10 and Equation 10.11.

Equation 10.10 $$\tilde{e}_{n,s} \leq e_{n,s,t} \leq \bar{e}_{n,s}$$

Equation 10.11 $$-\infty \leq h_{n,s,t} \leq +\infty$$

The flows in all passive branches are constrained by their capacities F_ℓ in every snapshot (Brown, Hörsch, and Schlachtberger 2018, 6). For example, the capacity of dispatch can also be optimised into store via a link connection, such that the controllable flow capacity is constrained by its nominal energy flow capacity given in Equation 10.12.

Equation 10.12 $$|f_{\ell,t}| \leq F_\ell \qquad \forall \ell, t$$

For the lines and the buses, the flow of power $f_{\ell,t}$ is defined by the reactance and the voltage difference across the components. For example, in AC network the difference in voltage angles $\theta_{n,t}$, at bus 0 and $\theta_{m,t}$ at bus 1 is divided by the series reactance x_l given in Equation 10.13 (PyPSA Developers 2021).

Equation 10.13 $$f_{l,t} = \frac{\theta_{n,t} - \theta_{m,t}}{x_l}$$

For nodal power balances

By applying Kirchhoff's Current Law, the constraint of the balance of power on each node is applied to produce Equation 10.14 below (PyPSA Developers 2021). The equation guarantees that the power balances at each bus n for each time t, where $d_{n,s,t}$, is the exogenous load at each node (load.p_set) and the incidence matrix K_{nl} for the graph takes values in $\{-1,0,1\}$ depending on whether the branch l ends or starts at the bus. $\lambda_{n,t}$ is the shadow price of the constraint such as the locational marginal price stored in network.bus.t.marginal_price. A full listing of the set notations is also given below in Equation 10.14.

Equation 10.14 $$\sum_s g_{n,s,t} + \sum_s h_{n,s,t} - \sum_s f_{n,s,t} - \sum_l K_{nl} f_{l,t} = \sum_s d_{n,s,t} \qquad \leftrightarrow \qquad w_t \lambda_{n,t}$$

Where the set notation is defined as follows:

Bus label: $n, m \in N = 0, \ldots |N| - 1$

Snapshot or time point label: $t \in T = 0, \dots |T| - 1$

Branch label: $l \in L = 0, \dots |L| - 1$

Generator and storage type labels: $s \in S = 0, \dots |S| - 1$

10.9. Non-linear power flow

After the energy system has been optimized for one year at an hourly interval using the optimal power flow, the non-linear power flow is conducted on the resulting dispatch. Since the optimal power flow solution does not differentiate between active and reactive power, the voltage magnitude variations at each bus are not considered in the simulation. The non-linear power flow is conducted either, on a snapshot or a selection of snapshots at once to determine to steady-state operating conditions such as voltage magnitude and power flows. Consequently, the non-linear power flow was used in the investigation to identify the lines and transformers that must be increased in rated power.

The operation of the power network within power quality requirements, such as the required voltage magnitude levels as new generators are added or the extension of lines, is critical (Brown, Hörsch, and Schlachtberger 2018, 5). The power flow is the calculation of the steady state solution of an electrical power network and the solution states the voltage and the power at each bus distributed across the network, which is performed using non-linear algebraic power equations at each node in the system.

In solving the power flow problem Kirchhoff Current Law is applied at each bus (Brown, Hörsch, and Schlachtberger 2018, 5–6). The impedances of the lines, transformers and shunt reactors at each bus are required for the calculation. The impedances are converted to admittance values. The active and reactive power at each bus is described using the admittance matrix in Equation 10.15 for an AC network.

Equation 10.15 (Brown, Hörsch, and Schlachtberger 2018, 5–6)

$$S_i = P_i + jQ_i = V_i I_i^* = V_i (\sum_j Y_{ij} V_j)^*$$

Where:

- $V_i = |V_i| e^{j\theta_i}$ is the complex voltage, whose rotating angle is taken relative to the slack bus i.
- V_j the complex voltage at bus j.
- Y_{ij} is the admittance matric based on the branch impedances and any shunt admittance attached to buses.
- I_i^* is the complex conjugate current at bus i.
- For the slack bus $i = 0$ it is assumed $|V_0|$ is given and that $\theta_0 = 0$; P and Q are to be found.
- For the PV buses, P and $|V|$ are given; Q and θ are to be found.

- For the PQ buses, P and Q are given: $|V|$ and θ are to be found.
- If PV and PQ are the sets of buses, then there are $|PV|$ + $2|PQ|$ real equations to solve:

$$\mathrm{Re}\left[V_i\left(\sum_j Y_{ij}V_j\right)^*\right]-P_i \quad =0\forall i\in PV\cup PQ$$

$$\mathrm{Im}\left[V_i\left(\sum_j Y_{ij}V_j\right)^*\right]-Q_i \quad =0\forall i\in PQ$$

10.10. Cost assumptions

To calculate the respective equivalent annual cost (EAC) of the system components, the capital cost of each element, an interest rate of 6% and marginal cost using *Equation 10.16* and *Equation 10.17* below (Fleischer 2017, 56). The capital costs are calculated using the capital cost per unit of installed capacity and the total optimized installed capacity of the component. The marginal costs are the product of the marginal cost per unit of energy produced and the annual energy generated by the component. Where (A_{tr}) is the annuity factor for the component's lifetime (t) and interest rate (r).

Equation 10.16 $$EAC = \frac{Capital\ cost}{A_{t,r}} + Marginal\ cost$$

Equation 10.17 $$A_{t,r} = \frac{1-\frac{1}{(1-r)^t}}{r}$$

Chapter 11 – Creation of scenarios and optimal power flow results

11.1. Creation of the scenario and model assumptions

Based on the assumptions in Chapter 9, the optimal power flow and non-linear power flow simulations were conducted for the Barbadian power system in the PyPSA-Barbados model (Andre Harewood and Fleischer 2020). As mentioned in the previous sections, the primary examination focused on simulating the T&D grid for the REF-100 scenario with the 80 MW cap on the utility solar PV resource used as the main scenario, labelled REF-100. The main REF-scenario created in the oemof-barbados model examined the reference case demand, with controlled charging of passenger EVs and cruise ships, labelled REF-100CEV. The uncontrolled charging was examined as separate scenarios, labelled as REF-100UEV. In keeping with specific requests by the Energy Division, fleet e-bus uncontrolled charging was added separately to the scenarios, labelled as REF-100CEVB and REF-100UEVB, as shown in Table 11.1 below.

Table 11.1. Summarizes the scenarios used to examine the impact of controlled and uncontrolled charging (Own Creation n.d) as used in (Andre Harewood and Fleischer 2020)*)*

Scenarios	Demand
REF-100CEV	Reference scenario demand, controlled charging of electric vehicles and cruise ships
REF-100CEVB	Reference scenario demand, controlled charging of electric vehicles, cruise ships, uncontrolled charging of electric buses
REF-100UEV	Reference scenario demand, uncontrolled charging of electric vehicles and cruise ships.
REF-100UEVB	Reference scenario demand, uncontrolled charging of electric vehicles, cruise ships and uncontrolled charging of electric buses

For the optimal power flow, active power values are used in the simulations; therefore, the load and generators power factor were assumed to be 1. The power factor was readjusted for the power flow optimization to 0.85 for the power values of load, generators, biomass plants, and pumped hydro storage. In the case of lines and transformers, the rated power of the component can be increased at a cost. However, increasing the power rating could be done by using a different line with a higher rated power value and another impedance value. Despite an increase in the rated power of the component, the technical specifications are unchanged.

11.2. Optimal power flow results

As detailed optimization of the energy system, including analysis of the wind and dispatchable renewables, was completed using the oemof-barbados model, no further analysis was conducted on optimizing the energy system. All such analyses can be seen in Sections 8.1 to 8.9. However, Table 11.2 below summarizes the results using the optimal power flow of PyPSA. The first column in the Table describes the maximum nominal power allocated for each bus, which was compared to the nominal power optimized for each bus in PyPSA for each scenario. Table 11.2 also serves to highlight the changes in the renewable dispatch with the addition of controlled versus uncontrolled charging of passenger transportation or electric buses. For example, based on the REF-100 scenario, the optimal power flow results for all the scenarios showed similar results to the oemof-barbados model, such that despite seasonal variation in the wind resource, as shown in Figure 7.1, the wind resource was the most used renewable resource optimized by the model.

With the addition of more uncontrolled charging of transportation either from the bus fleet charged off-peak or passenger transportation charged in the evening, more onshore wind resources are utilized as shown in Table 11.2. The highest installed capacities occur in the REF-100UCEVB scenario.

Table 11.3 summarizes the optimal power generation for each of the buses where the flexible dispatch is located. The maximum capacity of the bagasse, waste-to-energy and lithium batteries was utilized in all the scenarios. However, the maximum installed PHS was only utilized with the addition of the charging demand of the electric buses at the ST bus.

Table 11.2. Summarizing the optimal dispatch installed for all the scenarios (Own Creation n.d).

	REF (MW) Maximum Capacity	**REF-100CEV /MW)**	**REF-100 CEVB (MW)**	**REF-100UCEV (MW)**	**REF-100UCEVB (MW)**
Bus	p_nom_max	p_nom_opt	p_nom_opt	p_nom_opt	p_nom_opt
WA-pv-distributed	8.289	0.000	8.289	0.000	8.289
WP-pv-distributed	8.289	5.165	8.289	0.000	8.289
SG-pv-distributed	8.289	0.000	8.289	0.000	8.289
GAR-pv-distributed	8.289	0.000	8.289	0.000	8.289
BEL-pv-distributed	8.289	8.289	8.289	0.000	8.289
MS-pv-distributed	8.289	8.289	8.289	0.000	8.289
TY-pv-distributed	8.289	0.000	8.289	0.000	8.289
CEN-pv-distributed	8.289	8.289	8.289	8.289	8.289
RP-pv-distributed	16.293	0.000	16.293	3.161	16.293
WO-pv-distributed	16.293	0.000	16.293	16.293	16.293

	REF (MW) Maximum Capacity	REF-100CEV /MW)	REF-100 CEVB (MW)	REF-100UCEV (MW)	REF-100UCEVB (MW)
SW-pv-distributed	16.293	0.000	16.293	16.293	16.293
OW-pv-distributed	24.209	24.209	24.209	24.209	24.209
HAM-pv-distributed	25.837	0.000	25.837	25.837	25.837
TRT-pv-utility	10.000	0.000	0.000	0.000	0.000
NO-pv-utility	10.000	10.000	10.000	10.000	10.000
CAR-pv-utility	10.000	10.000	10.000	10.000	10.000
ST_pv-utility	10.000	10.000	10.000	10.000	10.000
CEN-pv-utility	20.000	20.000	20.000	20.000	20.000
WO_pv-utility	10.000	10.000	10.000	10.000	10.000
HAM-pv-utility	15.000	15.000	15.000	15.000	15.000
TRT-onshore	68.000	0.000	68.000	2.480	0.000
NO-onshore	100.000	0.000	3.701	0.000	0.000
CAR-onshore	94.000	75.973	53.321	0.000	90.224
OW-onshore	47.000	0.000	8.836	41.224	0.000
HAM-onshore	85.000	0.000	0.000	0.000	85.000

Table 11.3. Summarizes the flexible generation and storage for each scenario (Own Creation n.d).

	REF (MW) Maximum Capacity	REF-100CEV /MW)	REF-100 CEVB (MW)	REF-100UCEV (MW)	REF-100UCEVB (MW)
Flexible gen. & storage	p_nom_max	p_nom_opt	p_nom_opt	p_nom_opt	p_nom_opt
ST-phs	124.000	119.067	124.000	116.275	124.000
SG-battery	11.000	11.000	11.000	11.000	11.000
OW-bagasseBUK	25.000	25.000	25.000	25.000	25.000
ST-bagassePRT	25.000	25.000	25.000	25.000	25.000
OW-bagasseAND	25.000	25.000	25.000	25.000	25.000
ST-waste	27.000	27.000	27.000	27.000	27.000

Chapter 12 – Non-linear power flow results

For the non-linear power flow, the bus to which the pumped storage is connected was assumed to be a slack bus and an additional slack generator is connected to the same bus. All buses except for the slack bus were assumed to be PQ buses. Based on the optimal power flow results, a series of snapshots were selected based on the scenarios in Table 11.1, to represent the “worst-case” instances of the line loading, which ranged between 79% to above 100% in some instances, with the upper bounds indicating that the lines were well beyond carrying capacity and required replacing for a line-type with a higher capacity. For example, if a line has a 70% line loading, that line has 20% capacity remaining, approaching 100%, the line integrity is jeopardized and is prone to damage. For line loadings above 100%, this indicates the lines are overloaded. In Figures 12.1 – 12.2, 12.5 – 12.6, 12.9 - 12.10, 12.13 – 12.14, the colour code of the diagram ranges from green, red and white, with white indicating the lines with the most loading. A legend explaining the line loading in detail was included in each section. However, several buses/substations were anonymized in the report as requested by energy stakeholders.

12.1. Selection of snapshots

For the controlled charging, a sample of severe line loadings, with significant peaks in demand and generation, was observed at 10:00am, as shown in Table 12.1 below. For example, snapshot (210) corresponded to an instance with the highest wind power production in the system at that time interval of the year. Similarly, as cruise demand follows the seasonality in the wind resource, the demand from the cruise industry was also among the highest for the year. Also, with the addition of uncontrolled charging of the e-bus fleet, this period corresponds to the highest demand for e-bus fleet charging. Alternatively, snapshot (2332) represents an instance with low seasonal wind resources and low tourism demand but high flexible generation in the system.

Table 12.1. Summarizes the snapshots used to examine controlled charging of electric vehicles and uncontrolled, uncontrolled charging of electric bus fleet charging (Own Creation n.d)

Date	Snapshot	Description of Generation	Description of Demand
2030-01-27 10:00:00	210	High wind High solar	High cruise ship demand High E-bus charging demand

Date	Snapshot	Description of Generation	Description of Demand
		High pump storage High bagasse High waste-to-energy	
2030-10-19 10:00:00	2332	Lowest wind High solar PV High pump storage High bagasse Low waste-to-energy	Low cruise ship demand

Based on the results for the uncontrolled charging, snapshots 214 and 2206 were used for analysis (c.f. Table 12.2 below*), these are* similar to snapshots 210 and 2332, corresponding to similar peaks in generation and demand, respectively. However, as the charging profile of the uncontrolled charging passenger transportation was shifted, the maximum peak charging occurred between 16:00 hrs and 18:00 hrs., as opposed to between 10:00am to midday as shown in Harewood et al (2021, 123). Specifically, snapshot 214 was an instance in the energy system that corresponded to peak demand from passenger E-mobility evening charging in addition to the e-mobility demand from uncontrolled E-bus charging as explained in Section 7.8.1 of Chapter 7. A general description of the demand and generation for the snapshots was also detailed in Table 12.2

Table 12.2. Summarizes the snapshots used to examine the uncontrolled charging of electric vehicles, uncontrolled charging of electric bus fleet (Own Creation n.d)

Date	Snapshot	Generation	Demand
2030-01-27:16:00	214	High wind High solar PV High pump storage	High cruise ship demand
2030-10-03 16:00:00	2206	Lowest wind High solar PV High pump storage	Low cruise ship demand

12.2. Results: Controlled charging of electric vehicles

The snapshots' results, which examined controlled and uncontrolled charging, were shown as a series of line diagrams with a Table. For example, for snapshot 210 below, Figure 12.2 describes the line loading in the present T&D grid with the daily demand load, cruise ships and passenger e-mobility under controlled charging from the solar resources. Figure 12.1 describes the line loading with the daily demand load, cruise ships, passenger e-mobility, and the additional uncontrolled charging of the E-bus fleet. Table 12.3 compares the line loadings for both scenarios at snapshot 210.

Based on the line loading observed in snapshot 210 with the daily demand load, cruise ships and passenger e-mobility under the conditions of controlled charging, Figure 12.3 shows the load at the buses represented as load-p, in addition to the generation from renewable resources as gen-p and the storage inclusive of the batteries, PHS and flexible generation as storage-p. Figure 12.4 shows the load, generation, and storage of the buses with the addition of uncontrolled E-bus charging in snapshot 210. Table 12.5 numerically compares the load, renewable generation, and storage for both scenarios with and without the addition of electric buses. In all the tables and graphs, numerical values for the loads were shown as negative values to differentiate them from the sources of renewable generation, flexible/dispatchable, and storage generation. In addition, the renewable energy includes both the wind and solar PV resources. However, these were differentiated as the results were explained in detail.

For snapshot 210, the main lines that were overloaded were identified in Figure 12.2 and Figure 12.1 for visual representation. However, in keeping with requests by energy sector shareholders to maintain data anonymity, no other lines or buses were labelled for visual representation.

12.2.1. Results for snapshot 210

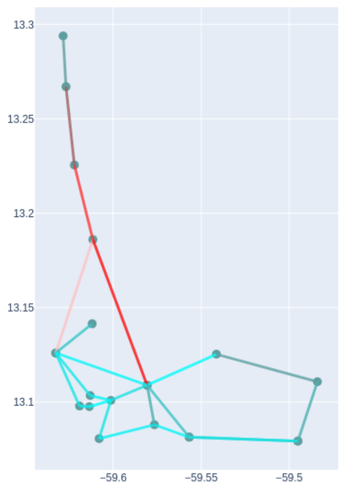

Figure 12.2. Summaries line loading for snapshot 210 for REF-100CEV scenario (Own Creation n.d)

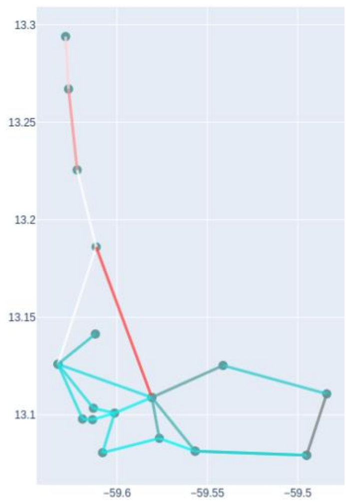

Figure 12.1. Summaries line loading for 210 for REF-100CEVB scenario (Own Creation n.d)

Table 12.3. Summarizes the colour for the line loading in Figure 12.2 and Figure 12.1 above.

Colour line	Loading (%)
White	200 - 300
Light red	150 -190
Red	100 -149
Red grey	60-99
Dark grey	40-59
Dark green	29-30
Green	0-28

The lines with the highest loading are white to red, with white being the highest, whereas lines with the lowest line loading are shown as green.

Table 12.4. Comparing the line loading for snapshot 210, with controlled charging EVs (REF-CEV) and the addition of the E-bus fleet (REF-CEVB) at the buses in the T&D network (Own Creation n.d)

Snapshot 210	Lines	REF-100CEV	REF-100CEVB
	line_1[9]	177	209.4
	line_3	21.9	2.9
	line_4	8	12.7
	line_5	3	7.8

[9] The lines loaded above capacity or the highest compared to the other lines were highlighted in red.. The labels for the lines are included in Figure 12.2 and Figure 1.3.

Snapshot 210	Lines	REF-100CEV	REF-100CEVB
	line_6	12.5	6.3
	line_7	7.6	7.5
	line_8	40.8	18.6
	line_9	105.6	128.1
	line_12	4.6	2.2
	line_13	30.8	30.8
	line_14	4.3	6.7
	line_15	9.2	11.6
	line_16	1.4	2.5
	line_17	3.6	7.4
	line_18	8.5	12.3
	line_19	27.2	48.6
	line_20	37.8	183.5
	line_21	121.7	281.4
	line_22	62.6	158.7
	line_24	0.2	11.4
	line_25	13.1	19.5
	line_26	22.4	29

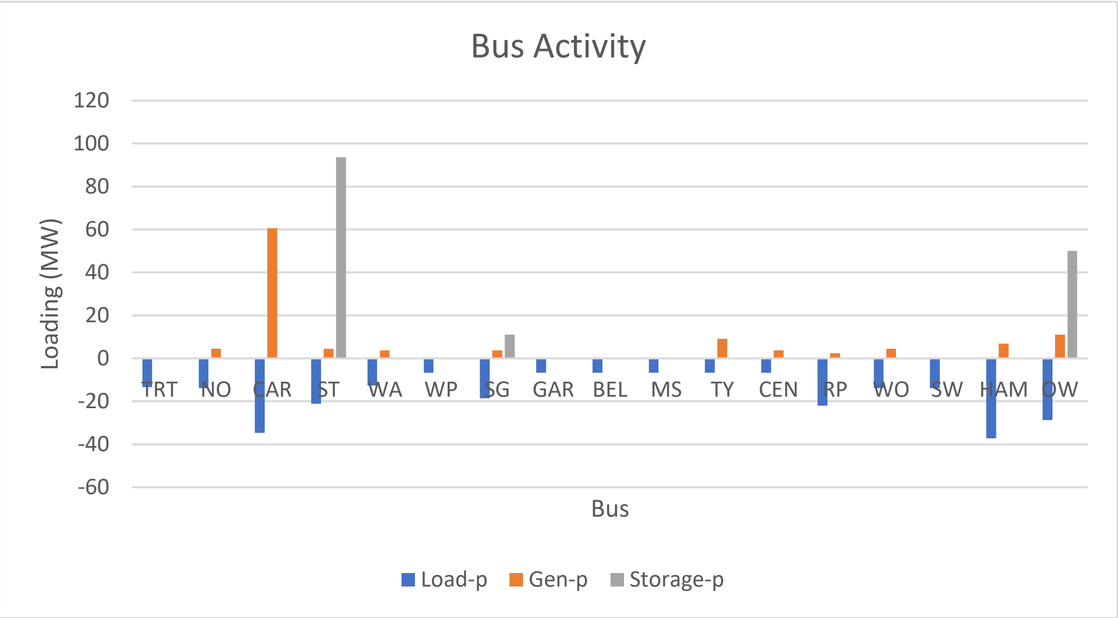

Figure 12.3. Summarizes the line loading, generation, and storage at the buses in REF-100CEV-210 scenario (Own Creation n.d)

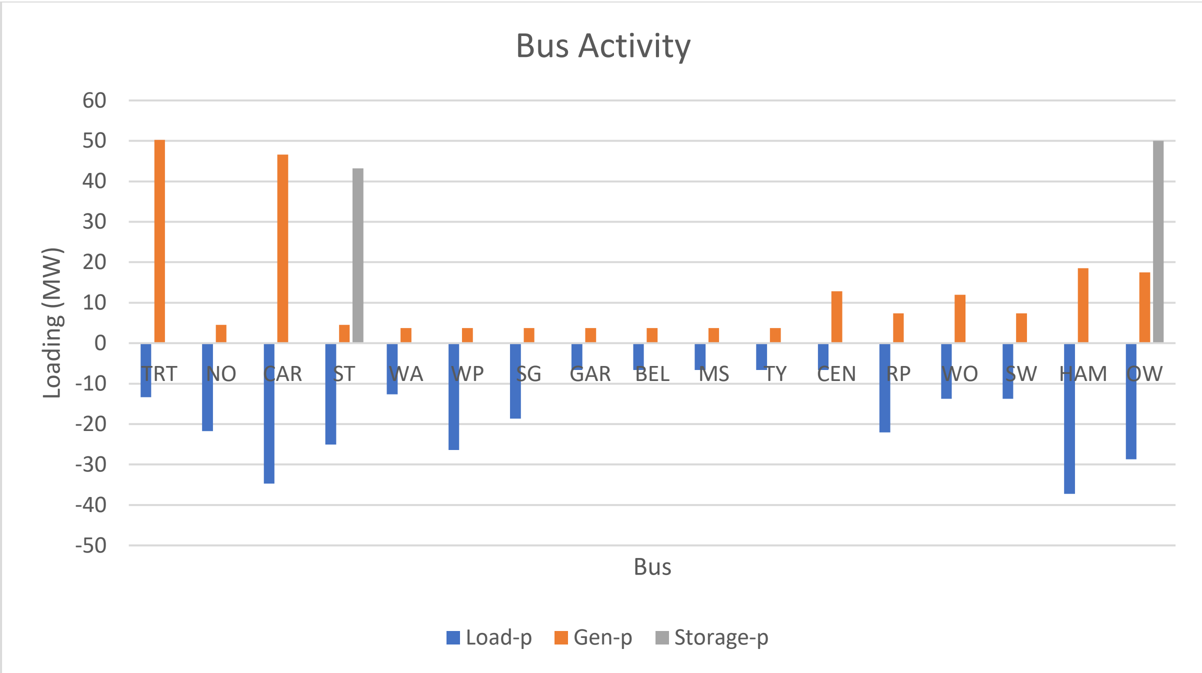

Figure 12.4. Summarizes the line loading, generation, and storage at the buses in REF-100-210CEVB scenario (Own Creation n.d)

Table 12.5 Comparing the load, storage and generation at each bus as shown in Figure 12.4 to 12.5. (Own Creation n.d)

	(210) REF-100CEV			(210) REF-100CEVB		
Bus	Load-p	Gen-p	Storage-p	Load-p	Gen-p	Storage-p
TRT	-13.38			-13.38	50.23	
NO	-13.79	4.54		-21.71	4.54	
CAR	-34.72	60.57		-34.72	46.60	
ST	-21.12	4.54	93.70	-25.08	4.54	43.2
WA	-12.62	3.77		-12.62	3.77	
WP	-6.63			-26.43	3.77	
SG	-18.63	3.77	11.00	-18.63	3.77	0
GAR	-6.63			-6.63	3.77	
BEL	-6.63			-6.63	3.77	
MS	-6.63			-6.63	3.77	
TY	-6.63	9.09		-6.63	3.77	
CEN	-6.63	3.77		-6.63	12.86	
RP	-22.05	2.35		-22.05	7.40	
WO	-13.77	4.54		-13.77	11.95	
SW	-13.77			-13.77	7.40	
HAM	-37.23	6.82		-37.23	18.56	
OW	-28.73	11.00	50.00	-28.73	17.53	50

12.2.1.1. Explanation REF-100CEV for snapshot 210

In the REF-100CEV scenario at snapshot 210, as mentioned above, high line loading was observed at lines 1,9,21 and 22 (c.f. Figure 12.2 and Table 12.4 above on pages 177 and 177-178, respectively). Notwithstanding, the buses with the highest loads were as follows: HAM (37.23 MW), CAR (34.7 MW), OW (28.7 MW), RG (22 MW) and SG (18.6 MW), as shown in Figure 12.3 on page 178 and Table 12.5 on page 179 above. These loads are expected since these buses are among the island's most populated areas, including the load from the controlled charging of e-mobility, in addition to the docking of the cruise ships at the SG bus.

In examining Figure 12.3, the load was met with a high share of centralized renewable generation in addition to flexible generation and storage. The most significant sources of flexible generation and storage were located at the ST and OW buses, as follows: OW-bagasse-Buckeley (25 MW), OW-bagasse-Andrews (25 MW), ST-bagasse-Portland (25 MW), ST-phs (41.7 MW), and ST-waste (27 MW).

The primary sources of renewable energy were onshore wind in the north of the island at the CAR bus, as CAR-onshore-wind (56 MW), in addition to solar PV resources distributed in the highest capacities at the OW, TY, HAM, CAR and WO buses as follows: OW-pv-distributed (11 MW), TY-pv-utility (9.09 MW), HAM-pv-utility (6.82 MW), CAR-pv-utility (4.54 MW) and WO-pv-utility (4.54 MW) (c.f. Figure 12.3 and Table 12.5 above). However, there are several instances of no renewable generation at the TRT, WP, GAR, BEL, MS and SW buses (c.f. Table 12.5)

The high line loading on lines 1, 21 and 22 can be attributed to pump hydro storage and flexible generation modelled as storage at the ST bus, specifically the ST-bagasse-Portland (25 MW), ST-waste (27 MW), ST-phs (41.7 MW) in addition to the onshore wind from the north of the island at the CAR bus, as CAR-onshore-wind (56 MW) with an installed capacity of utility PV as CAR-pv-utility (4.54 MW). The high line loading on line 9 is mainly attributed to the bagasse modelled as a storage technology at the OW bus as OW-bagasse-Buckeley (25 MW) and OW-bagasse-Andrews (25 MW). The results show that most of the utility-scale/onshore wind, flexible generation, and pump storage are mostly centralized at the buses that are not situated at sites of high demand, which causes high line loading in the 24 kV backbone T&D grid.

12.2.1.2. Explanation REF-100CEVB for snapshot 210

In the REF-100CEVB scenario at snapshot 210, a similar pattern of high line loading occurred on lines 1, 9, 21, 22 and 20, as shown in Figure 12.1 and Table 12.4 on pages 177 and 177-178, respectively above. At that instance on the grid, the load on the buses was similar to snapshot REF-

100CEV. Therefore, similar capacities of flexible generation and storage were utilized, as observed in snapshot 210-CEV, at the ST and OW buses in the form of OW-bagasse-Buckeley (25 MW), ST-bag (25 MW) and OW-bag (25 MW, with the addition of pump hydro storage as ST-phs (18 MW) (c.f. Figure 12.4 and Table 12.5 on page 179).

However, there was an increase in the load from the charging of E-buses at the Speighstown, Mangrove and Weymouth bus depots on the NO (21.71 MW), ST (21.71 MW) and WP (26.43 MW) buses, respectively, as shown in Figure 12.4 and Table 12.5 above. The seasonal wind resource peaked during that time of the year. In that instance, the load was met with more renewable generation, mainly from onshore wind energy at the TRT and CAR substations in the north of the island: TRT-onshore-wind (50.23 MW) and CAR-onshore-wind (42 MW), in addition to more distributed solar PV at the following buses: CAR (4.6 MW), GAR (3.77 MW), BEL (3.77 MW), MS (3.77 MW) and TY (3.77 MW). However, higher line loading was observed on lines 21 and 22 in addition to line 20 as the loads were satisfied with more utility-scale wind in the north of the island.

12.2.2. Results for snapshot 2332

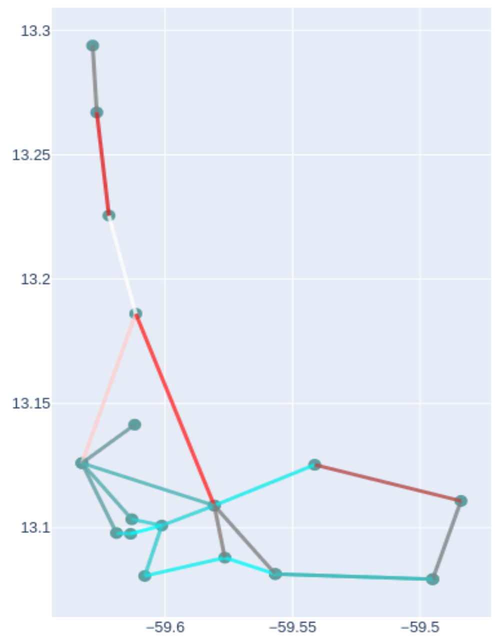

Figure 12.6.Summarizes the line loading in snapshot 2332 in the REF-100CEV scenario (Own Creation n.d)

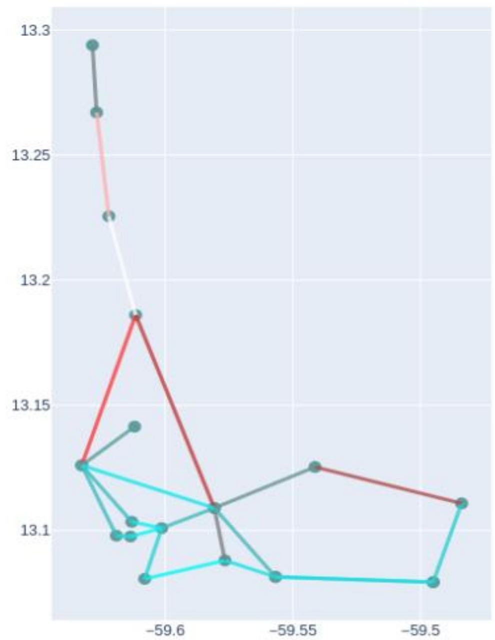

Figure 12.5. Summarizes the line loading in snapshot 2332 in the REF-100CEVB scenario (Own Creation n.d)

Table 12.6. Summarizes the colour for the line loading in Figure 12.6 and Figure 12.5.

Colour line	Loading (%)
White	200 - 300

Colour line	Loading (%)
Light red	150 -190
Red	100 -149
Red grey	60-99
Dark grey	40-59
Dark green	29-30
Green	0-28

The lines with the highest loading are white to red, with white being the highest, whereas lines with the lowest line loading are shown as green as follows.

Table 12.7. Summarizes the line loading at Snapshots 2332 with controlled charging of EVs and E-buses (Own Creation n.d).

Snapshot 2332	Lines	REF-100CEV	REF-100CEVB
	line_1[10]	181	124.7
	line_3	40.1	36.5
	line_4	33.6	25
	line_5	17.7	6.9
	line_6	33.8	26.7
	line_7	28.1	41.7
	line_8	82.1	68.8
	line_9	115.7	76.7
	line_12	6.8	10.7
	line_13	57	49.2
	line_14	2.8	1.6
	line_15	22	15.8
	line_16	4.8	3.2
	line_17	19.9	11.7
	line_18	44.6	25.1
	line_19	37.8	18
	line_20	49.9	46.9
	line_21	201.6	284.7
	line_22	88.6	170.8
	line_24	24.7	8.1
	line_25	26.8	14.6
	line_26	46.8	26.9

[10] The lines loaded above capacity or the highest compared to the other lines were highlighted in red.

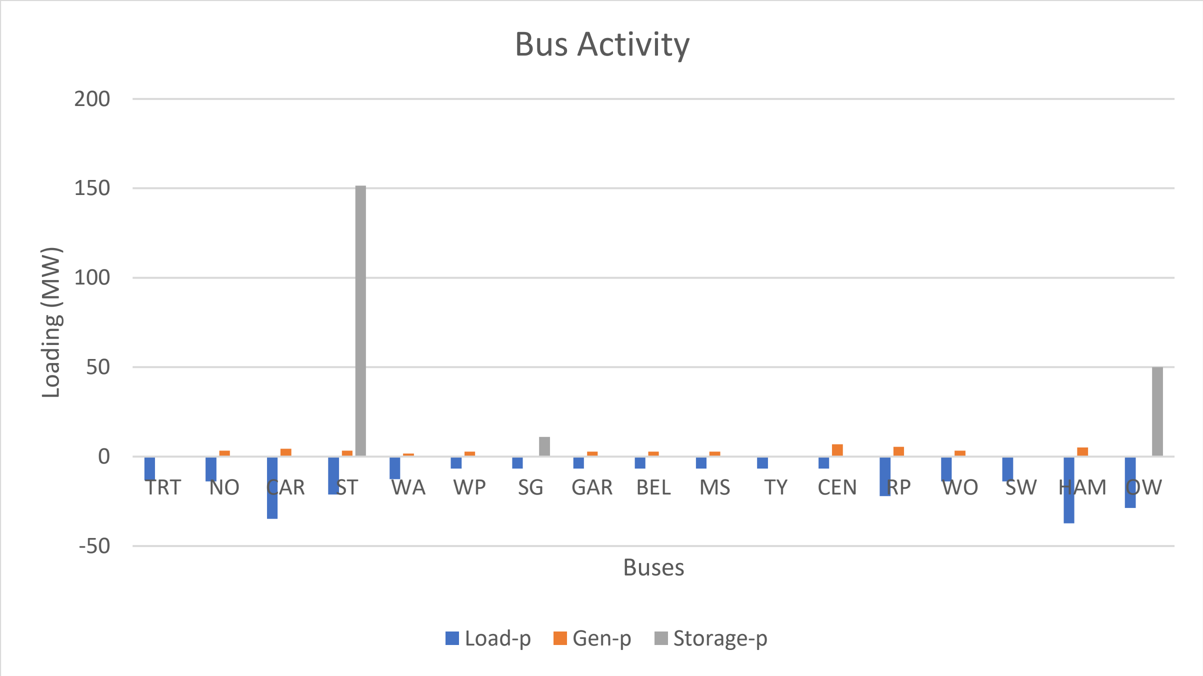

Figure 12.7. Summarizes the line loading, generation, and storage at the buses in snapshot 2332 for REF-100UCEV scenario (One creation n.d)

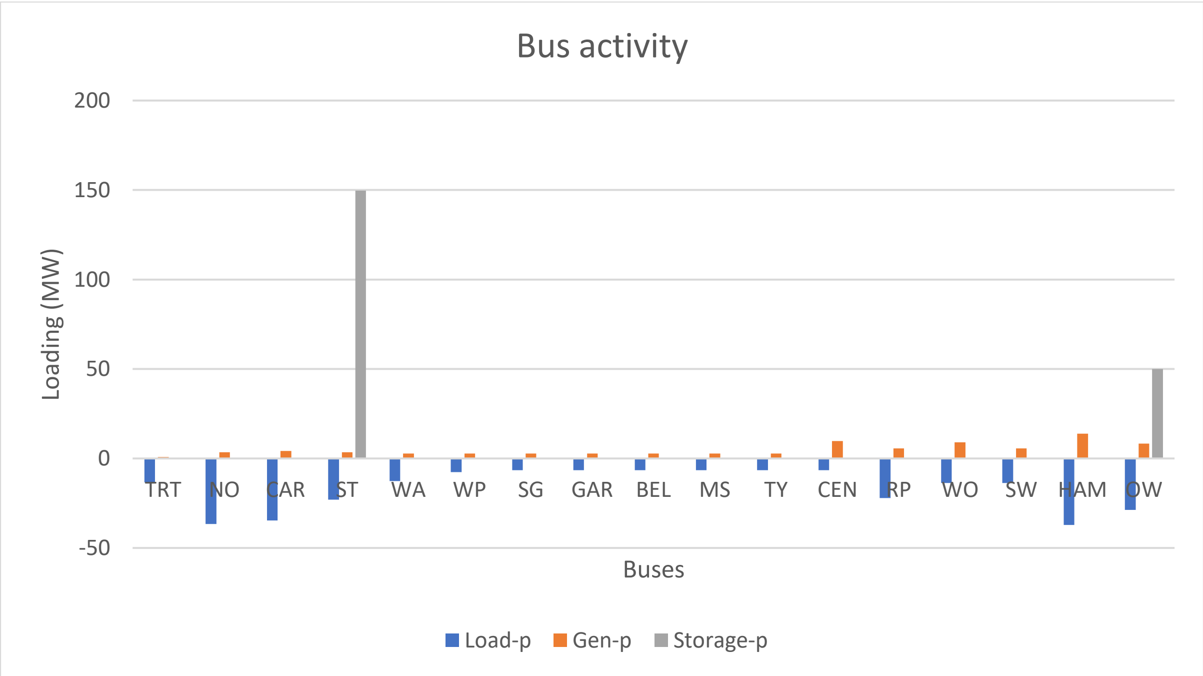

Figure 12.8. Summarizes the line loading, generation, and storage at the buses in snapshot 2332 for REF-100CEVB scenario (Own Creation n.d)

Table 12.8. Comparing the load, storage and generation at each bus as shown in Figure 12.9 to 12.8. (Own Creation n.d)

	2332-CEV			2332-CEVB		
Bus	Load-p	Gen-p	Storage-p	Load-p	Gen-p	Storage-p
TRT	-13.3807			-13.381	0.8023	
NO	-13.789	3.4136		-36.559	3.4134	
CAR	-34.7167	4.34339		-34.717	4.1115	
ST	-21.1157	3.4136	151.49	-23.096	3.4137	149.726
WA	-12.6203	1.64		-12.620	2.8293	
WP	-6.6252	2.82		-7.675	2.8293	
SG	-6.6252		11	-6.625	2.8293	
GAR	-6.6252	2.82		-6.625	2.8293	
BEL	-6.6252	2.82		-6.625	2.8293	
MS	-6.6252	2.82		-6.625	2.8293	
TY	-6.6252			-6.625	2.8293	
CEN	-6.6252	6.8272		-6.625	9.6566	
RP	-22.0453	5.56196		-22.045	5.5619	
WO	-13.7663	3.4136		-13.766	8.9756	
SW	-13.7663			-13.766	5.5619	
HAM	-37.2314	5.1204		-37.231	13.940	
OW	-28.7302		50	-28.730	8.3682	50

12.2.2.1. Explanation REF-100CEV and the REF-100CEVB scenarios for snapshot 2332

In the REF-100CEV and REF-100CEVB scenarios at snapshot 2332, the majority of the line loading occurred on lines 1, 9, 21 and 22, as shown in Figure 12.6, Figure 12.5 and Table 12.7 on pages 181 and 182 above.

As highlighted in snapshot 2332 of the REF-100CEV scenario, based on the population density, the buses with the highest loads for the residential demand and electric vehicle charging were: CAR, HAM, OW and ST. While there was a reduction in the cruise ship industry's electricity demand, most of the renewable energy generation was distributed and utility-scale solar PV since the seasonal wind resource was significantly reduced in this instance.

The high line loading on lines 21, 22, 9 and 1 is caused as the load was primarily met by flexible generation in the form of pump hydro storage (101.49 MW), bagasse (25 MW) and waste-to-energy (25 MW) at the ST bus, as shown in Figure 12.7 and Table 12.8 above. This is in addition to 11 MW of battery storage at the SG bus. Similarly, high line loading was observed on line 8 due to the centralized flexible dispatch at the OW bus - OW-bagasse-Buckley (25 MW) and OW-bagasse-Andrews (25 MW), although the line was not overloaded. Overall, as the load was met primarily by these centralized sources of flexible generation and storage, significant line loading on the 24 kV T&D grid network was caused.

With the addition of E-bus charging at snapshot 2332, there was an increase in the load from the Speightstown (37 MW), Weymouth (7.6 MW) and Mangrove (23 MW) bus depots on the NO, WP and ST (23 MW) buses (c.f. Table 12.8 above). Nonetheless, at that instance, as solar PV power production was at a peak, the load was met with more renewable generation in the form of distributed and utility scale solar PV, mainly at the SG (2.83 MW) and TY (2.83 MW) buses in addition to a small installed capacity of onshore utility-scale wind at the CEN (9.66 MW), WO (8.97 MW), SW (5.56 MW), HAM (13.94 MW) and OW (8.37 MW) buses, as opposed to additional flexible generation or storage (c.f. Table 12.8 above). As more renewable energy, particularly solar PV, was utilized at that instance, the storage and flexible generation at the ST bus (149.73 MW) was slightly reduced. The centralized flexible generation and storage remained critical for the entire system, which resulted in high line loading, although more distributed solar generation was utilized at that instance. As a result, there was a slight reduction in the line loading compared to the REF-100CEV scenario, as shown in Table 12.7 above.

12.3. Results: Uncontrolled charging of electric vehicles

12.3.1. Results for snapshot 214

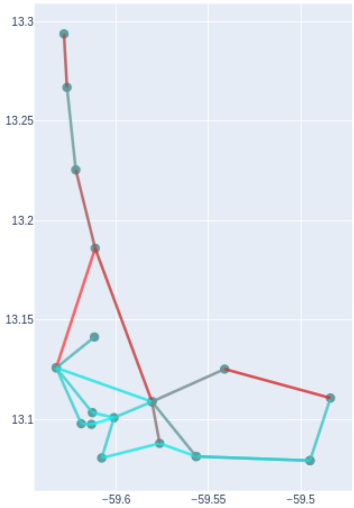

Figure 12.9. Summaries the line loading for the REF-100-UEV in snapshot 214 (Own Creation n.d)

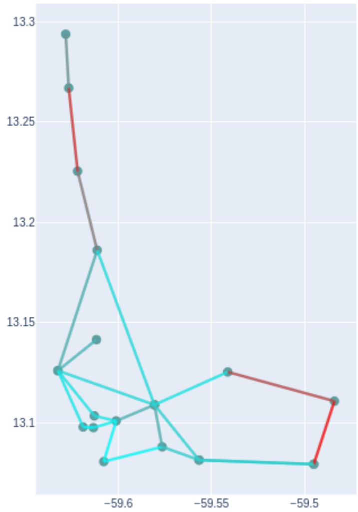

Figure 12.10. Summarizes line loading for the REF-100-UEVB in snapshot 214 (Own Creation n.d)

Table 12.9. Summarizes the colour for the line loading in Figure 12.9 and Figure 12.10.

Colour line	Loading (%)
White	200 – 300
Light red	150 -190
Red	100 -149
Red grey	60-99
Dark grey	40-59
Dark green	29-30
Green	0-28

The lines with the highest loading are white to red, with white being the highest, whereas lines with the lowest line loading are shown as green.

Table 12.10 Comparing the line loading for snapshot 214 with uncontrolled charging for both passenger transportation at the E-bus fleet (Own Creation n.d)

Snapshot 214	Lines	REF-100CEV	REF-100CEVB
	line_1[11]	125.8	32.5
	line_3	30	30
	line_4	18.5	12.3
	line_5	9.9	11
	line_6	15.9	31.2
	line_7	44.9	11.9
	line_8	84.3	70.1
	line_9	78.1	14.9
	line_12	8.4	20.6
	line_13	54.8	32.2
	line_14	10.2	4.2
	line_15	18.7	4.4
	line_16	1.4	7.3
	line_17	10	1.3
	line_18	18.5	9.9
	line_19	23.2	93.4
	line_20	71.1	43.1
	line_21	66.8	51.7
	line_22	40.3	77
	line_24	10	16.4
	line_25	22.2	22.4
	line_26	39.5	18.7

[11] The lines loaded above capacity or the highest compared to the other lines were highlighted in red.

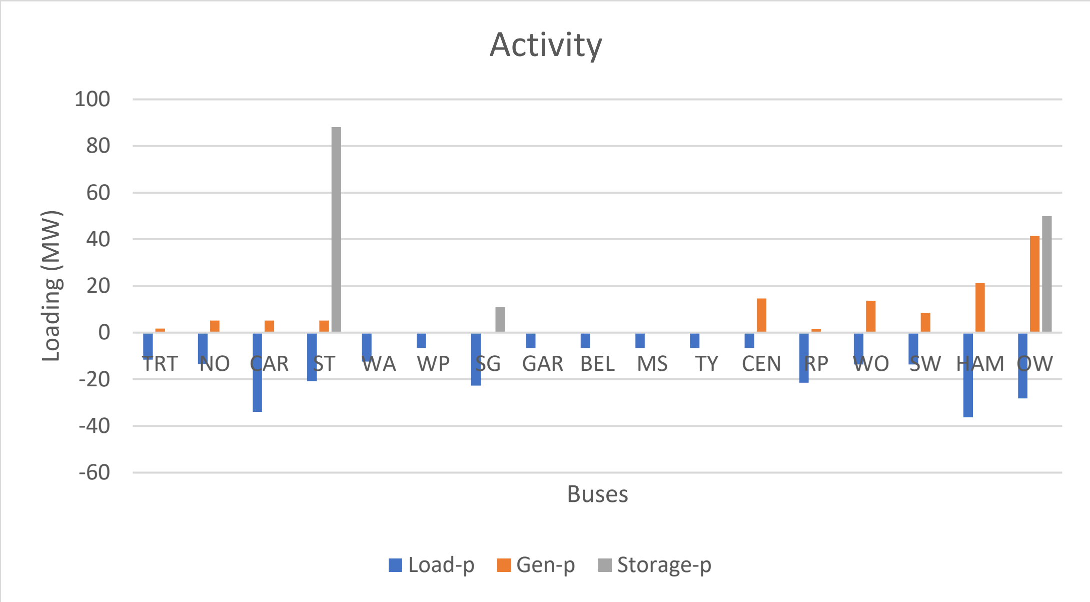

Figure 12.11. Summarizes the line loading, generation, and storage in snapshot REF-100-UCEV at snapshot 214 (Own Creation n.d)

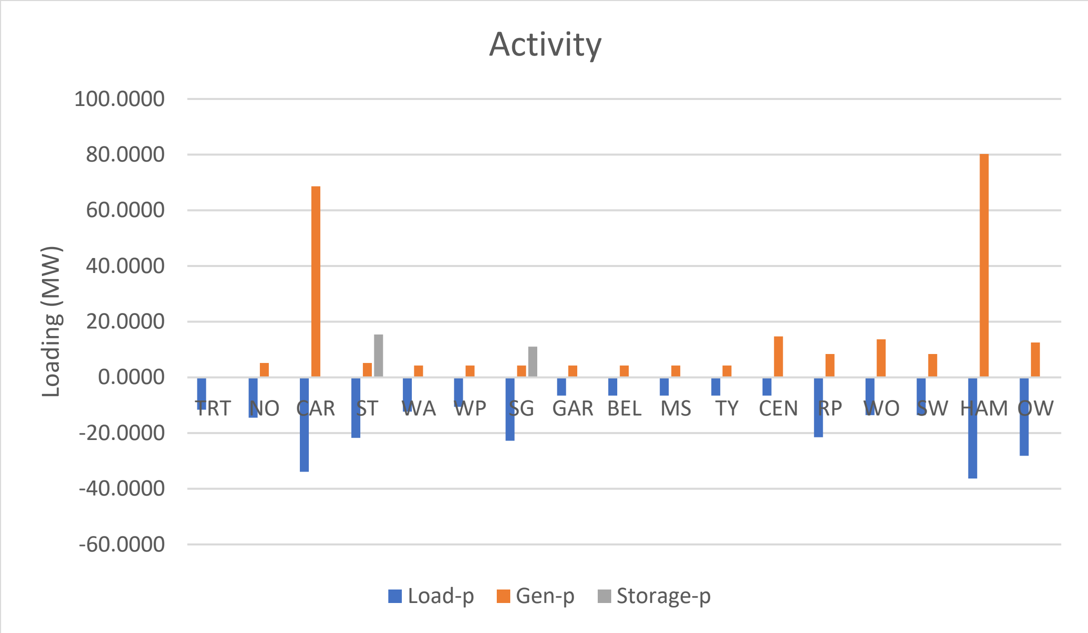

Figure 12.12. Summarizes the line loading, generation, and storage in snapshot REF-100-UCEVB at snapshot 214 (Own Creation n.d)

Table 12.11. Comparing the load, storage and generation at each bus as shown in Figure 12.11 and Figure 12.12 above (Own Creation n.d).

	(214) REF-100CEV			(214) REF-100CEVB		
Bus	Load-p	Gen-p	Storage-p	Load-p	Gen-p	Storage-p
TRT	-11.5679	1.7386		-11.5679	0.0000	
NO	-13.4652	5.1884		-14.4552	5.1884	
CAR	-33.8990	5.1884		-33.8990	68.5936	
ST	-20.7069	5.1884	88.1106	-21.6969	5.1884	15.3662
WA	-12.3381	0.0000		-12.3381	4.3004	
WP	-6.5938	0.0000		-10.5538	4.3004	
SG	-22.7114	0.0000	11.0000	-22.7114	4.3004	11.0000
GAR	-6.5938	0.0000		-6.5938	4.3004	
BEL	-6.5938	0.0000		-6.5938	4.3004	
MS	-6.5938	0.0000		-6.5938	4.3004	
TY	-6.5938	0.0000		-6.5938	4.3004	
CEN	-6.5938	14.6773		-6.5938	14.6773	
RP	-21.5259	1.6401		-21.5259	8.4537	
WO	-13.5929	13.6422		-13.5929	13.6422	
SW	-13.5929	8.4537		-13.5929	8.4537	
HAM	-36.3525	21.1879		-36.3525	80.1913	
OW	-28.1632	41.4629	50.0000	-28.1632	12.5606	

12.3.1.1. Explanation REF-100UCEV for snapshot 214

In snapshot 214 of the REF-100-UCEV scenario, the highest line loading occurred on lines 1,8,9,21 and 22, whereas for the REF-100-UCEVB, the highest line loading occurred on lines 8,19 and 22 (c.f. Figure 12.9, Figure 12.10 and Table 12.10 on pages 186 and 187). However, only line 1 of the REF-100-UCEV scenario was overloaded, whereas line 19 of the REF-100-UCEVB was the closest to maximum capacity.

In snapshot 214 of the REF-100-UCEV scenario, the buses with the highest load occurred on the following: HAM (36.4 MW), CAR (33.9 MW), OW (28.2 MW), SG (22.7 MW) and ST (20.7 MW). These loads are expected as these buses are located among the most populated areas of the island, which also includes the uncontrolled evening charging of e-mobility in addition to the ship-to-shore charging of the cruise ships at the ST bus.

For the REF-100-UCEV scenario, examining the load, generation and storage, Figure 12.11 on page 188 and Table 12.11 on page 189 above show that the energy system is mainly supported with storage and flexible generation at the ST bus – ST-phs (36 MW), ST-bagasse-Portland (25 MW), ST-waste (27 MW) and the OW bus – OW-bagasse-Buckeley (25 MW) and OW-bagasse-Andrews (25 MW). There was a smaller installed capacity of battery storage at the SG bus (11 MW). However, there were instances of no renewable generation in the form of distributed/utility solar PV or utility scale wind at several buses (c.f. Table 12.11 above). The highest volume of renewable energy generation was at the OW bus in the form of OW-pv-distributed (12 MW) and OW-onshore-wind (29.46 MW). Due to the centralized storage and flexible generation on the ST bus, high line loading was observed on lines 21, 9 and 1, although only line 1 was overloaded. A similar pattern was observed at the OW bus, which caused high line loading on line 8, which was not overloaded.

12.3.1.2. Explanation REF-100UCEVB for snapshot 214

With the addition of uncontrolled E-bus mobility in the REF-100-UCEVB, at that instance, there was an increase in the load at the NO bus (14 MW), ST bus (21.5 MW) and the WP bus (10.6 MW) for the Speighstown, Mangrove and Weymouth bus depots. In this instance, the load in the system was met with significantly higher shares of renewable energy generation across several buses such as the WA (4.30 MW), WP (4.30 MW), SG (4.30 MW), GAR (4.30 MW), BEL (4.30 MW), MS (4.30 MW), TY(4.30 MW) and RP (8.45 MW) in the form of distributed and utility-scale solar PV, as shown in Table 12.11 as opposed to flexible generation and storage at the ST bus –ST-phs (15 MW) and SG – SG-battery (11 MW). The highest renewable energy generation was at CAR bus – CAR-utility-onshore-wind (63 MW) and CAR-pv-utility (5.2 MW) in addition to HAM bus – HAM-onshore-wind (59 MW), HAM-pv-utility (7.8 MW), HAM-pv-distributed (13.4 MW). As there was more distributed renewable generation, there were fewer instances of high line loading than in the REF-UCEV scenario, except on lines 8 and 19, which are closer to the HAM bus and line 21, which is closer to the CAR bus, both with high shares of renewable generation primarily in the form of utility scale wind. However, line 19 had the highest line loading approach maximum capacity.

12.3.1.3. Results for snapshot 2206

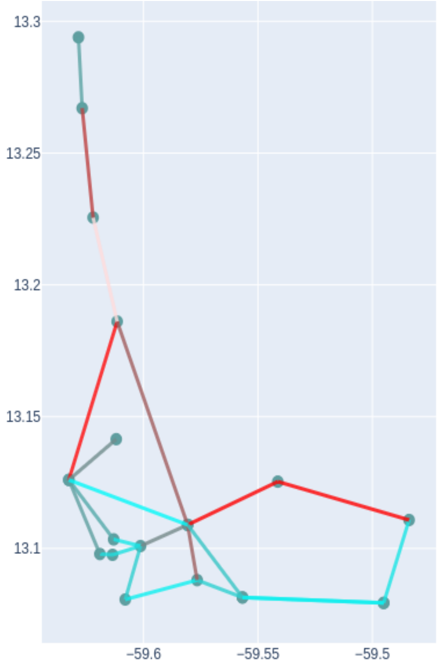

Figure 12.13.Summarizes snapshot REF-100-UEV- 2206 (Own Creation n.d)

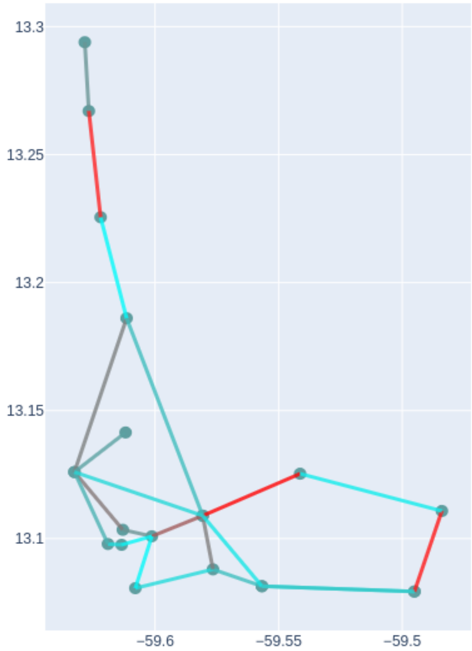

Figure 12.14. Summarizes snapshot REF-100-UEVB – 2206 (Own Creation n.d)

Table 12.12. Summarizes the colour for the line loading in Figure 12.13 and Figure 12.14.

Colour line	Loading (%)
White	200 – 300
Light red	150 -190
Red	100 -149
Red grey	60-99
Dark grey	40-59
Dark green	29-30
Green	0-28

The lines with the highest loading are white to red, with white being the highest, whereas lines with the lowest line loading are shown as green.

Table 12.13 Summarizing the line loading for the uncontrolled charging of passenger transportation and the E-bus for snapshot 2206 (Own Creation n.d)

Snapshot 2206	lines	REF-100CEV	REF-100CEVB
	line_1[12]	104	49.3
	line_3	44.4	36.2
	line_4	33.3	52.3
	line_5	8.9	42.1
	line_6	45	63.7
	line_7	99	101.2
	line_8	100	7.4
	line_9	62	25.3
	line_12	17	24.7
	line_13	62.2	50
	line_14	5.7	13.8
	line_15	18.7	2.4
	line_16	11.7	3
	line_17	12.7	13.2
	line_18	37	29.5
	line_19	10	110.1
	line_20	36	41.5
	line_21	186	1.8
	line_22	74.6	113.5
	line_24	2.4	15.3
	line_25	7.1	23
	line_26	22.6	9.7

[12] The lines loaded above capacity or the highest compared to the other lines were highlighted in red.

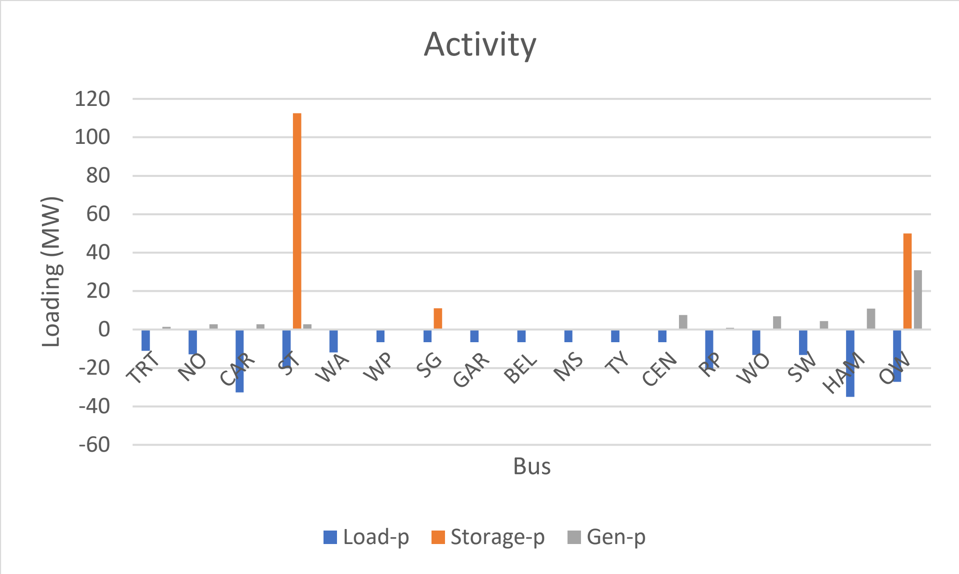

Figure 12.15. Summarizes the line loading, generation, and storage in snapshot REF-100-UEV-2206 Own Creation n.d)

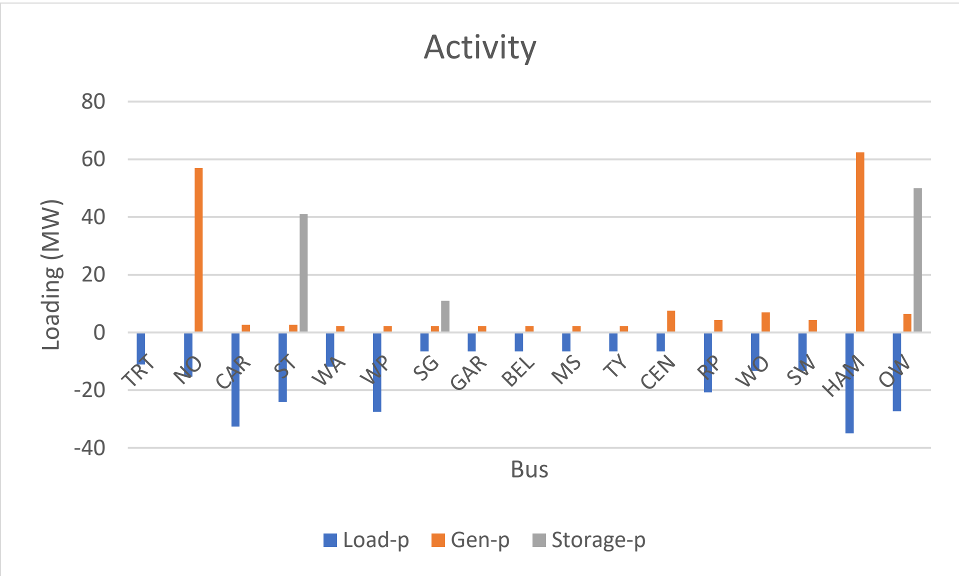

Figure 12.16. Summarizes the line loading, generation, and storage in snapshot REF-100-UEVB-2206 (Own Creation n.d)

Table 12.14. . Comparing the load, storage and generation at each bus as shown in Figure 12.6 and Figure 12.5 above (Own Creation n.d)

	(2206) REF-100UEV			(2206) REF-100UEVB		
Bus	Load-p	Storage-p	Gen-p	Load-p	Gen-p	Storage-p
TRT	-11.134		1.472	-11.134	0.000	
NO	-12.963		2.648	-15.339	56.945	

	(2206) REF-100UEV			(2206) REF-100UEVB		
CAR	-32.633		2.648	-32.633	2.648	
ST	-20.074	112.449	2.648	-24.133	2.648	40.991
WA	-11.901		0.000	-11.901	2.195	
WP	-6.545		0.000	-27.514	2.195	
SG	-6.545	11.000	0.000	-6.545	2.195	11.000
GAR	-6.545		0.000	-6.545	2.195	
BEL	-6.545		0.000	-6.545	2.195	
MS	-6.545		0.000	-6.545	2.195	
TY	-6.545		0.000	-6.545	2.195	
CEN	-6.545		7.492	-6.545	7.492	
RP	-20.721		0.837	-20.721	4.315	
WO	-13.325		6.963	-13.325	6.963	
SW	-13.325		4.315	-13.325	4.315	
HAM	-34.991		10.815	-34.991	62.480	
OW	-27.285	50.000	30.882	-27.285	6.411	50.000

12.3.1.4. Explanation REF-100UCEV for snapshot 2206

At snapshot 2206, for the REF-100UEV scenario, the highest line loading was on lines 1,7,8 and 21 (c.f. Figure 12.13 on page 191 and Table 12.13 on page 192).

For the REF-100UEV scenario, the buses with the highest loads were the HAM, CAR, RP and ST buses, which correspond to the areas with the highest residential demands and the evening charging of the EVs based on the population density. Similar to snapshot 214, in this instance, the system was mainly supported with flexible generation and pump hydro storage at the ST bus from ST-bagasse-Portland (25MW), ST- waste (27 MW) and ST-phs (60.45 MW), which overloaded lines 1 and 21. The high line loading on lines 7 and 8 can be primarily attributed to the centralized flexible generation at the OW bus - OW-bagasse-Buckeley (25 MW) and OW-bagasse-Andrews (25 MW).

The primary renewable energy generation was distributed, and utility-scale solar PV on the TRT (1.47 MW), NO (2.65 MW), CAR (2.65 MW), ST (2.65 MW), CEN (7.49 MW), RP (0.837 MW), WO (6.96 MW), SW (4.315 MW), and HAM (10.82 MW) buses, as shown in Table 12.14 above, with the highest renewable generation on the OW bus – OW-onshore-wind (24.47 MW) and OW-pv-distributed (6.411 MW), which also contributed in lines 7 and 8 approaching maximum capacity. However, there are several instances of no renewable generation at the WA, WP, SG, GAR, BEL, MS and TY buses. Consequently, the load was met, mostly with centralized flexible generation or storage at the OW and ST buses. Therefore, high line loading was caused in the 24 kV T&D grid.

12.3.1.5. Explanation REF-100UCEVB for snapshot 2206

In the REF-100-UEVB scenario, the highest line loading occurred on lines 7, 19 and 22. (c.f. Figure 12.14 on page 191 and Table 12.13 on page 192). The additional charging of the E-bus fleet increases the load, with the highest load occurring at Weymouth (27.5 MW), Mangrove (24.1 MW), and Speighstown (15.3 MW) on the WP, ST, and NO buses.

In comparison to the REF-100UEV scenario, the load was met with more renewable energy generation in the form of additional distributed and utility-scale solar PV at the NO (2.20 MW), WA (2.20 MW), WP (2.20 MW), SG (2.20 MW), GAR (2.20 MW), BEL (2.20 MW), MS (2.20 MW), TY (2.20 MW), RP (4.32 MW), HAM (10.81 MW) buses with the highest share of renewable energy from the utility-scale wind in the form of NO-onshore-wind (54.3 MW) and HAM-onshore-wind (51.7 MW) at the NO and HAM buses respectively (c.f. Table 12.14).

As shown in Table 12.13 and Figure 12.13 and Figure 12.14, there is a change in the pattern of the line loading; for example, due to the use of significant utility-scale wind at the HAM bus (51.7 MW) with distributed solar PV (10.81 MW) (c.f. Table 12.14), there was high line loading, most notable on line 19. Similarly, the high line loading line 22 can be attributed to the combined centralized renewable generation at the NO bus – NO-pv-distributed (2.20 MW) and NO-onshore-wind (54.3 MW). Similar to the REF-100 UEV scenario, the high line loading on line 7 can be attributed to the centralized flexible generation at the OW bus - OW-bagasse-Buckeley (25 MW) and OW-bagasse-Andrews (25 MW).

Despite the addition of the E-bus fleet in the REF-100UEVB scenario, there were fewer instances of high line loading/overloaded lines, as the load was met with more distributed renewable generation across the 24 kV grid. More importantly, the results highlight the impact of distributed vs. centralized generation, as with distributed generation, there is less line loading in the 24 kV T&G network.

12.4. Discussion

12.4.1. Power flow

With increased demand due to increased electrification of transportation from the E-buses, more onshore utility scale wind was utilized in the model, with some of the highest capacities utilized from the North of the island at the TRT and CAR buses/substations. With the addition of uncontrolled charging of passenger transportation and the E-bus charging off-peak, higher installed capacities of wind resources were utilized at both the CAR and HAM substations in addition to higher installed capacities of PHS compared to scenarios with controlled charging transportation. However, as extensive energy system optimization was conducted in Chapter 8 and discussed in Chapter 9, no further optimization was conducted using PyPSA's power flow optimization. As examined in Chapter 9, the waste-to-energy and biomass resources were utilized as highly dispatchable/flexible generation in the model, which was simulated based on Government policy directions at the time. However, the dynamic operation of the technologies used to generate electricity from these resources is simply impossible, and the GoB should consider other flexible electricity generation technologies, as mentioned in Chapter 9.

12.4.2. Non-Linear power flow

As explained in Chapter 13 – Section 13.1, most of the load was at substations located within the parishes of St. Michael, Christ Church with high demands at the following individual substations of ST, HAM and OW, as indicated by the Population Census 2010, these were among the most populated areas on the island. Also, the ST and HAM buses were the charging locations for the E-bus fleet for the Mangrove and Weymouth bus depots, respectively. Furthermore, most of the population and areas of high demand are in the centre of the island. In contrast, the snapshots show that most renewable generation, such as large-scale utility scale wind, is centralized in the North as TRT, NO CAR substations, notwithstanding significant wind resources are located within the south and east of the island as observed at the HAM substations. In addition, flexible generation, such as bagasse and waste-to-energy, is also centralized and located on OW and ST buses. In contrast, the pump storage was located at the ST bus.

Consequently, except for the solar-PV distributed resources, most of the renewable dispatch is centralized. The high line loadings observed in the snapshots can be attributed to the effect of low decentralized power generation, which becomes more apparent with increasing transportation electrification. When the demand in the energy system was met with either centralized dispatchable/flexible generation or storage situated in a few buses/substations as opposed to more distributed renewable generation closer to the sites of demand, the line loading was significantly higher. No more is this evident when examining the impact of electrification in the transportation sector during low renewable resource availability periods. High line loading was observed as large centralized dispatchable generation or storage that was heavily utilized, as these resources are located only at the ST and OW substations. This was also the case during periods of reduced wind resource availability when the flexible generation and pump storage were heavily utilized in the system, as observed in snapshots 2206 and 2332. When the demand is met with more distributed renewable resources closer to sites of high demand, the line loading is reduced regardless of the charging profile for vehicular transportation. This was also mainly observed in snapshot 214, which shows the lowest line loading even with the addition of the e-bus fleet, as a more distributed renewable energy resource closer to the demand sites was utilized rather than centralized generation sources.

As Chapter 9 in Section 9.3 mentions, in the case of dispatchable generation, flexible generation provided in the form of smaller decentralized units, such as biogas plants, can be located on substations with high populations and, thus, higher loads, such as HAM and OW. This is recommended for further research in future investigations as the model is used to support policy planning in Barbados. Notwithstanding, as mentioned in Section 9.3, flexible distributed generation will require more grid management and ancillary services, which was beyond the scope of this investigation at this time.

Table 10.4 and 10.5 from Chapter 10 were shown below as Table 12.15 and Table 12.16 for convenience and discussing the results.

Table 12.15. Maximum capacity of the AC overhead lines in MW (University of Iowa 2024).

Distance (km)	11 kV	24 kV	69 kV	110 kV	220 kV	380 kV
10	18.5	88	728	1850	7401	22080
20	9.3	44	364	925	3700	11040
30	6.2	29	243	617	2467	7360
40	4.6	22	182	463	1850	5520
50	3.7	18	146	370	1480	4416
60	3.1	15	121	308	1233	3680
70	2.6	13	104	264	1057	3154
80	2.3	11	91	231	925	2760
90	2.1	10	81	206	822	2453
100	1.9	9	73	185	740	2208

Table 12.16. Summarizes the line lengths as measured in QGIS (Own Creation n.d).

Lines	Length /km
line_17	0.91311
line_6	2.994493
line_7	6.900041
line_4	3.928713
line_5	1.770078
line_16	1.915918
line_18	4.235383
line_1	8.528311
line_3	3.787369
line_14	4.371421
line_12	6.549023
line_10	7.768178
line_13	2.753956
line_19	4.924158
line_9	14.28804
line_15	3.147802
line_8	7.161569
line_20	4.603591
line_21	4.705206
line_22	5.603993
line_26	5.741249

The non-linear power flow highlights the importance of modelling the energy system at a high spatial resolution to understand how the generation meets the demand at every time interval. Furthermore, understanding where generation sources are relative to demand is essential for future policy planning, especially for significant, decentralized generation sources.

The non-linear power flow shows that several lines on the 24 kV grid will require upgrading to higher line capacities to accommodate higher shares of renewables, flexible generation, and storage for the 100% RE system. Table 12.15 shows the maximum line capacity calculated for each line type based on distance in kilometres.

The snapshots analyzed in Sections 12.2 and 12.3 for conditions of controlled and uncontrolled charging showed that based on distance in km, several of these lines were overloaded, as highlighted in red as follows: lines 1 and 21,22 in the north of the island; lines 6 and 9 in the centre of the island; lines 8, 7, 19 in the south-east of the island. Specifically, lines 1,7,8,19,21,22 were above the maximum capacity of 24 kV for lines less than 10 km, with line 9 exceeding the maximum capacity of for lines between 10-20 km in length.

Based on modelling results and calculations, the minimum grid expansion requirement to support a 100% RES is to upgrade the current 24 kV grid to 69 kV at the minimum. However, analysis of the snapshots highlighted the pattern of high line loading, as the demand was met with flexible generation at the ST or OW buses with utility-scale wind resources in the north and south-east of the island.

Therefore, this study recommends the installation of two additional lines to connect the wind resources, PHS and flexible generation in the north and south-east of the island. Specifically, the study recommends the first line, as shown in Figure 12.17, to connect the wind resources represented as dots in the east of the island and the PHS. In addition, a second line, proposed as shown in Figure 12.18, connects the flexible generation and wind resources at the OW bus south-east of the island to the PHS. Ultimately, the new proposed T&D grid would be structured as shown in Figure 12.19 below, with the system providing additional support based on the n-1 security principle, which adds additional security to the system in the event of the failure of one or multiple sections, there will always be two ways to reach a point in the grid, thereby maintaining the operation of the entire system.

These two lines are recommended to be installed as 110 kV based on the calculations in Table 10.4 above. These provide support in the event of failure of critical parts of the grid and connect the primary source of generation and storage to the rest of the system. Although a minimum 69 kV line expansion in the existing backbone 24 kV T&D grid is the minimum required, the study recommends an expansion of 110 kV for both the existing T&D grid and the additional lines, as this upgrade ensures that the T&D grid has the capacity and security to support the final 100% RES.

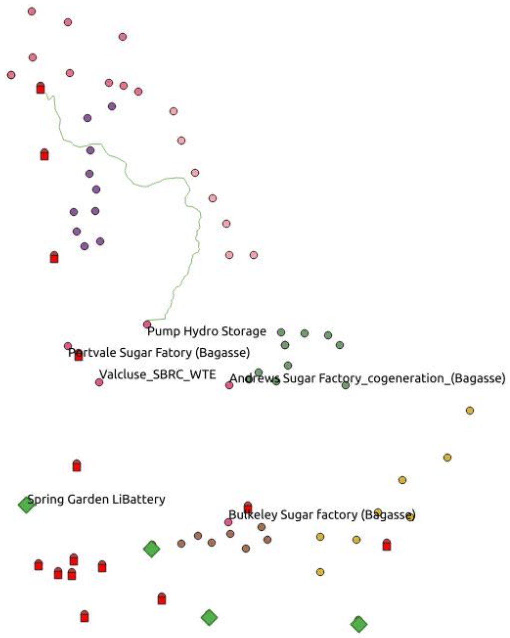

Figure 12.17. Show the addition of the first line from NO bus in the north of the island to the PHS (Own Creation n.d).

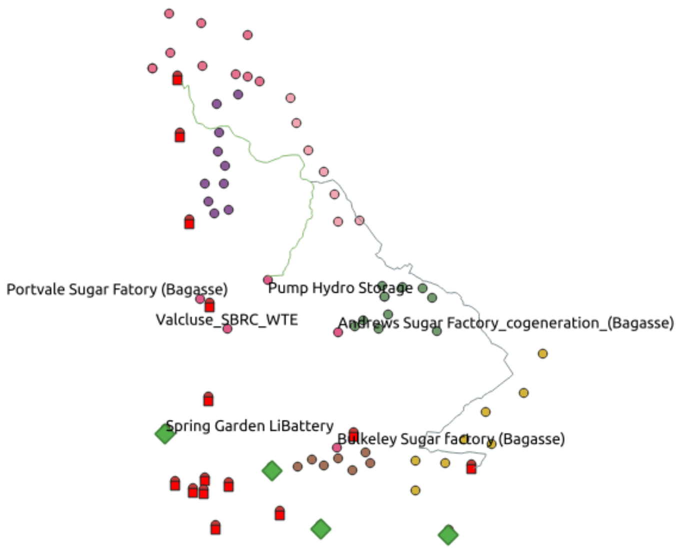

Figure 12.18. Summarizes the second additional line running from the PHS to the south-east of the island (Own Creation n.d).

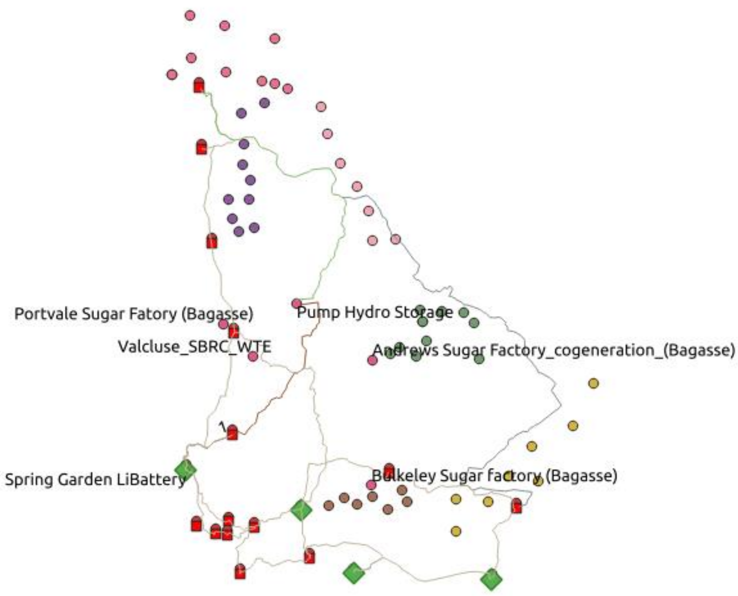

Figure 12.19. Summarizes the new grid with the additional lines and the existing the T&D network (Own Creation n.d).

12.5. Conclusion of power system modelling

A complete examination of the 24 kV T&D grid to higher line capacities of 69 kV and 110 kV was not possible at this stage of the investigation due to time constraints. Nonetheless, a detailed examination of loads, in addition to GIS mapping of substations and lines, was completed. The shape files for the grid expansion, including substations and lines drawn in QGIS, can be loaded in PyPSA for future modelling investigation on the Barbadian power system by the Division of Energy without jeopardizing data privacy and security.

This investigation, as an open-source initiative, provides a transparent and trustworthy start for examining the grid expansion for a 100% RES. The openness of this investigation allows for external examination by energy sector stakeholders, fostering a sense of inclusion in the process. The model results, assumptions, and data are open for external examination by energy sector stakeholders, which is an improvement over previous investigations on the power grid conducted using closed black box models. The Barbadian power grid can support a 100% RE system with grid reinforcements based on the results and calculations.

The results show that the minimum line expansion option for the 24 kV T&D network is 69 kV. However, the best option is to upgrade the entire 24 kV T&D backbone grid to 110 kV and add two 110 kV lines, as shown in Figures 12.19 and 12.20 above. Future studies will more accurately determine the least cost expansion options for expanding the lines in the Barbadian power system, including a detailed description of the final costs of the grid expansion for the 100% renewable energy system. Consequently, this investigation did not achieve the final system costs, including line replacement. Regarding grid expansion costs, Hirth et al. (2015) recommend 35% to 50% of the total generation costs. However, a fully detailed engineering study is required to describe these costs accurately within the context of the Barbados 100% renewable energy system, which can be done with the model in the future. More importantly, the PyPSA Barbados model provides a reasonable basis for more thorough investigations following this study to support policy planning in Barbados, which is the intention of the Energy Division and the GoB.

Chapter 13 – Final Conclusion

The results show that the transition to a 100% renewable energy system will significantly benefit Barbadian society in reduced LCOE, with most being socio-economic with broader participation of the society in the energy transition. Residential or sub-utility scale solar PV will enable and may be the only price point for many members of society to participate. However, community energy projects can enable economic participation in the energy transition at a lower initial investment cost than the sub-utility scale. Syncing the charging of E-mobility with renewable resources, especially solar resources, should be pursued by the GoB as this reduces the need for more expansive dispatchable units. Provided the technical and geological studies are completed to validate the design of the PHS facility, PHS is the cheaper storage option for Barbados. Notwithstanding, a combination of both technologies can be used with batteries for quick instantaneous response, but with the PHS providing the bulk of the storage requirements.

Investment in bagasse as an energy source for the sake of the island's sugar legacy at the expense of more flexible dispatch options should be reconsidered by the GoB. Any dispatchable technologies used in the 100% renewable energy system must be decentralized and highly flexible. As the results of the PyPSA show, having a more significant centralized generation will result in more line loading and require extensive grid expansion. However, with grid expansion, as outlined in Chapter 12, the system can support a 100% renewable energy system with additional security to the entire system. The decentralized generation will pose challenges for ancillary services and grid management. Despite challenges in data availability, the Barbadian energy system can be modelled with open-source source modelling tools. QGIS was used successfully to map the power grid to a high degree of detail, and that data was modelled for the backbone T&D grid in PyPSA. Due to time constraints and the need for more information, specifically online costs for Barbados, the investigation did not investigate replacing the lines with higher-capacity lines and the costs of that grid expansion for the 100% renewable energy system.

Nonetheless, the model can and will be used in the following investigations on grid expansion with more detailed analysis from an engineering perspective. Thus, with the Energy Division's approval, an open-source modelling framework was completed to inform policy planning within the SID state of Barbados. More importantly, these results and data are open for third-party external scrutiny and evaluation.

Bibliography

Aho, Jacob, Andrew Buckspan, Jason Laks, Paul Fleming, Yunho Jeong, Fiona Dunne, Matthew Churchfield, Lucy Pao, and Kathryn Johnson. 2012. 'A Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control'. In *2012 American Control Conference (ACC)*, 3120–31. IEEE. https://ieeexplore.ieee.org/abstract/document/6315180/.

Alleyne, Askia. 2014. '100% Renewable Electricity System for Barbados: The Solar Resource in Barbados'. Final Course Report RNEM 6010. RNEM6010 – Energy Economics. Bridgetown, Barbados: The University of the West Indies Cave Hill Campus.

Alves, M., R. Segurado, and M. Costa. 2020. 'On the Road to 100% Renewable Energy Systems in Isolated Islands'. *Energy* 198 (May):117321. https://doi.org/10.1016/j.energy.2020.117321.

AMEC. 2010. 'Environmental Impact Assessment the Barbados Light & Power Company Limited Lamberts East Wind Farm Generating Station'. Final report with addendum to address comments received TC101601. Mississauga, Ontario: AMEC Earth & Environmental.

Andersson, Oskar. 2021. 'Inclusion of Wind Turbines into Frequency Support Services: Exploring Frequency Stability Issues and Comparing Regulation Power Market Products'. https://www.diva-portal.org/smash/record.jsf?pid=diva2:1529906.

Baratieri, M., P. Baggio, B. Bosio, M. Grigiante, and G. A. Longo. 2009. 'The Use of Biomass Syngas in IC Engines and CCGT Plants: A Comparative Analysis'. *Applied Thermal Engineering* 29 (16): 3309–18. https://doi.org/10.1016/j.applthermaleng.2009.05.003.

Barbados Society of Technologists in Agriculture. 2010. 'Sugar At The Cross-Roads: BSTA's View On The Sugar Industry'. *Business Barbados* (blog). 17 March 2010. https://businessbarbados.com/industries/agriculture/sugar-at-the-cross-roads-bstas-view-on-the-sugar-industry/.

Bauwens, Thomas, Boris Gotchev, and Lars Holstenkamp. 2016. 'What Drives the Development of Community Energy in Europe? The Case of Wind Power Cooperatives'. *Energy Research & Social Science*, Energy Transitions in Europe: Emerging Challenges, Innovative Approaches, and Possible Solutions, 13 (March):136–47. https://doi.org/10.1016/j.erss.2015.12.016.

Beeck, Nicole van. 1999. *Classification of Energy Models*. FEW Research Memorandum. Operations research.

Bhattacharyya, Subhes, and Govinda Timilsina. 2010a. 'A Review of Energy System Models'. *International Journal of Energy Sector Management* 4 (November):494–518. https://doi.org/10.1108/17506221011092742.

———. 2010b. 'Modelling Energy Demand of Developing Countries: Are the Specific Features Adequately Captured?' *Energy Policy* 38:1979–90. https://doi.org/10.1016/j.enpol.2009.11.079.

Blechinger, P., R. Seguin, C. Cader, P. Bertheau, and Ch. Breyer. 2014. 'Assessment of the Global Potential for Renewable Energy Storage Systems on Small Islands'. *Energy Procedia*, 8th International Renewable Energy Storage Conference and Exhibition (IRES 2013), 46 (January):294–300. https://doi.org/10.1016/j.egypro.2014.01.185.

BL&P. 2014. 'Integrated Resource Plan (IRP) 2012'. Bridgetown, Barbados: Barbados Light and Power Co. Ltd.

BNOCL. 2021. 'Exploration and Production – Barbados National Oil Company Ltd.' *Exploration and Production* (blog). 2021. http://bnocl.com/services/exploration-and-production/.

Bohm, Sönke. 2019. 'An Introduction to the renpassG!S Energy System Simulation Model, Adjusted to the Country Cases of Morocco, Jordan and Tunisia'. Discussion Papers ISSN: 2192-4597. Discussion Papers Volume 10. Flensburg, Germany: Europa-Universität Flensburg: Centre for Sustainable Energy Systems.

BPI. 2020. 'Port Statistics 2010-2019'. Port Authority of Barbados.

Briguglio, Lino. 1995. 'Small Island Developing States and Their Economic Vulnerabilities'. *World Development* 23 (9): 1615–32. https://doi.org/10.1016/0305-750X(95)00065-K.

Brown, Tom, Jonas Hörsch, and David Schlachtberger. 2017a. ‘PyPSA: Python for Power System Analysis’. *arXiv Preprint arXiv:1707.09913*.

———. 2017b. ‘Python for Power System Analysis (PyPSA): Free Software for Planning Energy Systems with High Shares of Renewables’. In *1st International Conference on Large-Scale Grid Integration of Renewable Energy in India*.

———. 2018. ‘PyPSA: Python for Power System Analysis’. *Journal of Open Research Software* 6 (January):4. https://doi.org/10.5334/jors.188.

Brown, Tom, Hörsch, Jonas, and Schlachtberger, David. 2020. ‘Python for Power System Analysis (PyPSA) Version 0.17.0’. Zenodo. https://doi.org/10.5281/ZENODO.786605.

Buchinger, Josef, David Ince, Leisa Perch, and Brigitte Hatvan. 2018. ‘Barbados Sustainable Energy Industry Market Assessment Report’. Final Report 7000002430. Bridgetown, Barbados: Government of Barbados: Ministry of Environment and Drainage: Policy, Research, Planning and Information Unit. https://www.ccreee.org/wp-content/uploads/2020/06/barbados_market_assessment_report_-_final_2018-03-19.pdf.

Cabrera, Pedro, Henrik Lund, and José A. Carta. 2018. ‘Smart Renewable Energy Penetration Strategies on Islands: The Case of Gran Canaria’. *Energy* 162:421–43. https://doi.org/10.1016/j.energy.2018.08.020.

Callender, Victor. 2013. Barbados Light and Power EV Pilot Project.

Chang, Miguel, Jakob Zink Thellufsen, Behnam Zakeri, Bryn Pickering, Stefan Pfenninger, Henrik Lund, and Poul Alberg Østergaard. 2021. ‘Trends in Tools and Approaches for Modelling the Energy Transition’. *Applied Energy* 290 (May):116731. https://doi.org/10.1016/j.apenergy.2021.116731.

Chaudhary, Priyanka, and M. Rizwan. 2018. ‘Voltage Regulation Mitigation Techniques in Distribution System with High PV Penetration: A Review’. *Renewable and Sustainable Energy Reviews* 82 (February):3279–87. https://doi.org/10.1016/j.rser.2017.10.017.

Chen, A. A., A. J. Stephens, R. Koon Koon, M. Ashtine, and K Mohammed-Koon Koon. 2020. ‘Pathways to Climate Change Mitigation and Stable Energy by 100% Renewable for a Small Island: Jamaica as an Example’. *Renewable and Sustainable Energy Reviews* 121 (April):109671. https://doi.org/10.1016/j.rser.2019.109671.

Child, Michael, Claudia Kemfert, Dmitrii Bogdanov, and Christian Breyer. 2019. ‘Flexible Electricity Generation, Grid Exchange, and Storage for the Transition to a 100% Renewable Energy System in Europe’. *Renewable Energy* 139 (August):80–101. https://doi.org/10.1016/j.renene.2019.02.077.

Child, Michael, Alexander Nordling, and Christian Breyer. 2017. ‘Scenarios for a Sustainable Energy System in the Åland Islands in 2030’. *Energy Conversion and Management* 137:49–60. https://doi.org/10.1016/j.enconman.2017.01.039.

Christian Stoebich. 2016. Site visit and assessment of pump storage in Barbados.

Clarke, Roland. 2016. ‘Renewable Energy Options for Barbados and the Rest of the Caribbean’. Presented at The University of the West Indies Cave Hill Campus, Barbados, Bridgetown, September 10.

Connolly, D., H. Lund, B. V. Mathiesen, and M. Leahy. 2011. ‘The First Step towards a 100% Renewable Energy-System for Ireland’. *Applied Energy*, The 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, held in Dubrovnik September/October 2009, 88 (2): 502–7. https://doi.org/10.1016/j.apenergy.2010.03.006.

Connolly, D., Henrik Lund, Brian Mathiesen, and Martin Leahy. 2010. ‘A Review of Computer Tools for Analyzing the Integration of Renewable Energy into Various Energy Systems’. *Applied Energy* 87 (April):1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.

Ćosić, Boris, Goran Krajačić, and Neven Duić. 2012. ‘A 100% Renewable Energy System in the Year 2050: The Case of Macedonia’. *Energy*, 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environmental Systems, SDEWES 2011, 48 (1): 80–87. https://doi.org/10.1016/j.energy.2012.06.078.

Cross, Sam, David Padfield, Risto Ant-Wuorinen, Phillip King, and Sanna Syri. 2017. ‘Benchmarking Island Power Systems: Results, Challenges, and Solutions for Long Term Sustainability’. *Renewable and Sustainable Energy Reviews* 80 (December):1269–91. https://doi.org/10.1016/j.rser.2017.05.126.

Daly, Jack, and Karina Fernandez-Stark. 2017. *Barbados in the Cruise Tourism Global Value Chain*. https://doi.org/10.13140/RG.2.2.36014.20802.

Division of Energy. 2021. 'History of Hydrocarbon Production in Barbados'. History of Hydrocarbon Production in Barbados. 2021. http://www.energy.gov.bb/web/history-of-hydrocarbon-production-in-barbados.

Dominković, Dominik Franjo, Greg Stark, Bri-Mathias Hodge, and Allan Schrøder Pedersen. 2018. 'Integrated Energy Planning with a High Share of Variable Renewable Energy Sources for a Caribbean Island'. *Energies* 11 (9): 2193.

Dorotić, Hrvoje, Borna Doračić, Viktorija Dobravec, Tomislav Pukšec, Goran Krajačić, and Neven Duić. 2019. 'Integration of Transport and Energy Sectors in Island Communities with 100% Intermittent Renewable Energy Sources'. *Renewable and Sustainable Energy Reviews* 99:109–24. https://doi.org/10.1016/j.rser.2018.09.033.

Downes, Darrin, Nilandu Mamingi, Alexis Lescott, and Laron Alleyne. 2017. 'ESTIMATION OF THE PASS-THROUGH EFFECT OF INTERNATIONAL FOOD AND ENERGY PRICES ON DOMESTIC PRICES: THE CASE OF BARBADOS', CBB Working Paper, .

Droege, Peter. 2012. *100 Per Cent Renewable: Energy Autonomy in Action*. 1st ed. Routledge. https://www.routledge.com/100-Per-Cent-Renewable-Energy-Autonomy-in-Action/Droege/p/book/9781849714716.

Duić, Neven, and Maria da Graça Carvalho. 2004. 'Increasing Renewable Energy Sources in Island Energy Supply: Case Study Porto Santo'. *Renewable and Sustainable Energy Reviews* 8 (4): 383–99. https://doi.org/10.1016/j.rser.2003.11.004.

Erdinc, Ozan, Nikolaos G. Paterakis, and João P. S. Catalão. 2015. 'Overview of Insular Power Systems under Increasing Penetration of Renewable Energy Sources: Opportunities and Challenges'. *Renewable and Sustainable Energy Reviews* 52 (December):333–46. https://doi.org/10.1016/j.rser.2015.07.104.

Espinasa, Ramón, Christiaan Gischler, Malte Humpert, Camila Gonzalez Torres, and Carlos Sucre. 2016. 'Achieving Sustainable Energy in Barbados': Energy Dossier. IDB-Technical Note (TN)- 1077. Bridgetown, Barbados: Inter-American Development Bank. https://publications.iadb.org/publications/english/document/Achieving-Sustainable-Energy-in-Barbados-Energy-Dossier.pdf.

Faulstich, M., H. Foth, C. Calliess, O. Hohmeyer, K. Holm-Müller, M. Niekisch, and M. Schreurs. 2011. 'Pathways towards a 100% Renewable Electricity System'. *Berlin, Germany: German Advisory Council on the Environment*.

Ferroukhi, Rabia, Alvaro Lopez-Peña, Ghislaine Kieffer, Divyam Nagpal, Diala Hawila, Arslan Khalid, Laura El-Katir, and Salvatore Vinci. 2016. 'Renewable Energy Benefits: Measuring the Economics'. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency.

Fischer, Boris, Shan Martin, Philipp Brosche, Peter Loepelmann, Alireza Rezaeian, Mohamed Sayed, and Stefan Hauptmann. 2020. 'GRIDLOADS – NEUE ANFORDERUNGEN AN TRIEBSTRANG- UND STRUKTURKOMPONENTEN VON WEA AUS NETZSTÜTZENDEN REGELUNGSVERFAHREN'. Abschlussbericht 0324192A/B. Kasse: Fraunhofer IEE. https://www.mesh-engineering.de/images/Publications/MesH/Abschlussbericht_GridLoads_final.pdf.

Fleischer, Christian. 2017. 'Optimizing the Power System Investments and Electricity Dispatch Costs to Meet the Electrical Demand of the Islands of Mahè, Praslin and La Digue Using Only Renewable Energy Sources'. Master's Thesis. Flensburg, Germany: Europa-Universität Flensburg: Centre for Sustainable Energy Systems.

Forrest, John. 2020. 'CBC User Guide'. Open Source Initiative. www.coin-or.org/Cbc/cbcuserguide.html.

FTC. 2020. 'Fair Trading Commission, Barbados - Decision on Feed-in-Tariffs for Renewable Energy Technologies above 1MW and up to 10 MW'. FTCUR/DECFIT/2020-01. Decisions & Orders: Bridgetown, Barbados: Fair Trading Commission. https://www.ftc.gov.bb/index.php?option=com_content&task=view&id=19&Itemid=46.

Fuso Nerini, Francesco, Ilkka Keppo, and Neil Strachan. 2017. 'Myopic Decision Making in Energy System Decarbonisation Pathways. A UK Case Study'. *Energy Strategy Reviews* 17 (September):19–26. https://doi.org/10.1016/j.esr.2017.06.001.

Gaber H. Saif, Ahmed, Seddik Wahid, and Mohamed Ali. 2020. 'Pyrolysis of Sugarcane Bagasse: The Effects of Process Parameters on the Product Yields'. *Materials Science Forum* 1008 (July):159–67. https://doi.org/10.4028/www.scientific.net/MSF.1008.159.

GE Energy Management. 2015. 'Barbados Wind and Solar Integration Study'. Executive Summary Report. Bridgetown, Barbados: GE Energy Management Energy Consulting.

General Assembly. 2015. 'United Nations: Transforming Our World: The 2030 Agenda for Sustainable Development'. Tech. Rep. 1.

General Electric. 2021. 'GE Grid Study'. Division of Energy. http://www.ge.com/news/press-releases/ge-led-study-reaffirms-barbados-light-powers-renewable-power-integration.

Gils, Hans Christian, and Sonja Simon. 2017. 'Carbon Neutral Archipelago – 100% Renewable Energy Supply for the Canary Islands'. *Applied Energy* 188:342–55. https://doi.org/10.1016/j.apenergy.2016.12.023.

Gils, Hans, Sonja Simon, and Rafael Soria. 2017. '100% Renewable Energy Supply for Brazil-The Role of Sector Coupling and Regional Development'. *Energies* 10 (November). https://doi.org/10.3390/en10111859.

Gioutsos, Dean Marcus, Kornelis Blok, Leonore van Velzen, and Sjoerd Moorman. 2018. 'Cost-Optimal Electricity Systems with Increasing Renewable Energy Penetration for Islands across the Globe'. *Applied Energy* 226 (September):437–49. https://doi.org/10.1016/j.apenergy.2018.05.108.

GOB, Government of Barbados. 2019. 'Barbados National Energy Policy 2019 - 2030'. Official policy document BNEP. Barbados National Energy Policy. Trinity Business Complex - Bridgetown, Barbados: The Ministry of Energy & Water Resources.

———. 2023. 'Sustainable Energy Investment Programme (Energy Smart Fund 2) – Energy.Gov.Bb'. National Government Agency Website. 2023. https://energy.gov.bb/our-projects/sustainable-energy-investment-programme-energy-smart-fund-2/.

GOB, Stantec, and Castalia. 2010. 'Sustainable Energy Framework (SEF) for Barbados'. Final Report - Volume 1. ATN/OC-11473-BA. Barbados, Bridgetown: Inter-American Development Bank. https://bajan.files.wordpress.com/2011/07/barbados-sustainable-energy-framework-vol-i.pdf.

Griffiths, Steven. 2017. 'Renewable Energy Policy Trends and Recommendations for GCC Countries'. *Energy Transitions* 1 (1): 3. https://doi.org/10.1007/s41825-017-0003-6.

Guezello, Alin. 2018. 'Energy Balance: Reunion Island 2017'. ISSN : 2551-1920. Reunion Island: Public Local Company Energies Réunion. https://energies-reunion.com/wp-content/uploads/2015/01/BER-2017-ed-2018-english.pdf.

Hall, Lisa M. H., and Alastair R. Buckley. 2016. 'A Review of Energy Systems Models in the UK: Prevalent Usage and Categorization'. *Applied Energy* 169 (May):607–28. https://doi.org/10.1016/j.apenergy.2016.02.044.

Hansen, Kenneth, Christian Breyer, and Henrik Lund. 2019. 'Status and Perspectives on 100% Renewable Energy Systems'. *Energy* 175 (May):471–80. https://doi.org/10.1016/j.energy.2019.03.092.

Harewood, André. 2013. 'The Final 100% Renewable Energy System for Barbados'. Research Assignment: RNEM 6010: Energy Economics 100% Renewable Energy System for Barbados: Solar Energy Potential of Barbados and the Hourly Production Curve. Bridgetown, Barbados: The University of the West Indies Cave Hill Campus.

Harewood, Andre, and Christian Fleischer. 2020. '100-Barbados PyPSA Model'. PyPSA model. Flensburg, Germany.

Harewood, Andre, Simon Hilpert, and Franziska Dettner. 2021. 'Open Source Modelling of Scenarios for a 100% Renewable Energy System in Barbados Incorporating Shore-to-Ship Power and Electric Vehicles'. *Energy for Sustainable Development*, International Energy Initiative, 68 (June):120–30. https://doi.org/10.1016/j.esd.2022.03.004.

Haynes, Bryan. 2015. 'Overview and Analysis of the Energy Market'. BREA Presentation. Barbados Renewable Energy Association (BREA) Energy Stakeholder Meeting. Barbados, Bridgetown: Barbados Renewable Energy Association (BREA).

———. 2019. Transition to a 100% Renewable Energy System Barbados.

———. 2021a. 'E-Mobility and Transportation Information'.

———. 2021b. The implications of the Global Pandemic on Policy Planning in the Energy Sector of Barbados Interview by André Harewood.

———. 2023. Investment into a 100% renewable energy system and the future of the Barbadian energy sector.

Haynes, Bryan, and David Ince. 2019. 'Barbados National Energy Policy 2019 - 2030'. National Energy Policy. Bridgetown, Division of Energy, Trinity Business Complex, Barbados: The Ministry of Energy & Water Resources.

Healey, Victoria, Laura Beshilas, Kamyria Coney, and Gary Jackson. 2020. 'Energy Snapshot - Barbados'. NREL/FS-7A40-76636. National Renewable Energy Lab. (NREL), Golden, CO (United States). https://www.osti.gov/biblio/1659992.

Heard, B. P., B. W. Brook, T. M. L. Wigley, and C. J. A. Bradshaw. 2017. 'Burden of Proof: A Comprehensive Review of the Feasibility of 100% Renewable-Electricity Systems'. *Renewable and Sustainable Energy Reviews* 76 (September):1122–33. https://doi.org/10.1016/j.rser.2017.03.114.

Helgesen, Per Ivar. 2018. 'Top-Down and Bottom-Up: Combining Energy System Models and Macroeconomic General Equilibrium Models. 2013'. *Accessed Date* 17.

Henderson, Vince. 2013. 'SIDS DOCK: Facilitating the TRANSFORMATION of the SIDS Energy SECTOR TO ENABLE CLIMATE CHANGE ADAPTATION: "25-50-25 By 2033"'. Presented at the SIDS 2014 INTER-REGIONAL PREPARATORYMEETING, Barbados, August 26. https://sustainabledevelopment.un.org/content/documents/3779henderson.pdf.

Henry, Legena, Jacqueline Bridge, Mark Henderson, Kevin Keleher, Megan Kirchhoff, Geoff Goodwin, Deborah Namugayi, et al. 2015. *Key Factors around Ocean-Based Power in the Caribbean Region, via Trinidad and Tobago. Renewable and Sustainable Energy Reviews*. Vol. 50. https://doi.org/10.1016/j.rser.2015.04.115.

Hilpert, S, C. Kaldemeyer, U. Krien, S. Günther, C. Wingenbach, and G. Plessmann. 2018. 'The Open Energy Modelling Framework (Oemof) - A New Approach to Facilitate Open Science in Energy System Modelling'. *Energy Strategy Reviews* 22 (November):16–25. https://doi.org/10.1016/j.esr.2018.07.001.

Hilpert, Simon, Franziska Dettner, and Ahmed Al-Salaymeh. 2020. 'Analysis of Cost-Optimal Renewable Energy Expansion for the near-Term Jordanian Electricity System'. *Sustainability* 12 (22): 9339.

Hilpert, Simon, Stephan Günther, Krien Uwe, Guido Pleßmann, Frauke Wiese, Clemens Wingenbach, and Cord Kaldemeyer. 2017. 'Addressing Energy System Modelling Challenges: The Contribution of the Open Energy Modelling Framework (Oemof)'. *PLoS ONE*, February. https://doi.org/10.20944/preprints201702.0055.v1.

Hilpert, Simon, and André Harewood. 2021. 'Oemof-Barbados'. Flensburg: ZNES Flensburg. https://github.com/znes/oemof-barbados.

Hinds, Kristina, and Jeremy Stephen. 2017. 'Fiscal Crises in Barbados: Comparing the Early 1990s and the Post-2008 Crises'. *Third World Thematics: A TWQ Journal*, December 1–21. https://doi.org/10.1080/23802014.2017.1408425.

Hiremath, R. B., S. Shikha, and N. H. Ravindranath. 2007. 'Decentralized Energy Planning; Modeling and Application—a Review'. *Renewable and Sustainable Energy Reviews* 11 (5): 729–52. https://doi.org/10.1016/j.rser.2005.07.005.

Hirth, Lion, Falko Ueckerdt, and Ottmar Edenhofer. 2015. 'Integration Costs Revisited – An Economic Framework for Wind and Solar Variability'. *Renewable Energy* 74:925–39. https://doi.org/10.1016/j.renene.2014.08.065.

Hoffman, Steven M., and Angela High-Pippert. 2005. 'Community Energy: A Social Architecture for an Alternative Energy Future'. *Bulletin of Science, Technology & Society* 25 (5): 387–401. https://doi.org/10.1177/0270467605278880.

Hohmeyer, Olav. 2017. 'Economic Analysis to Facilitate the Establishment of a Stable Price for Electricity from Renewable Sources'. Draft Final Report MEE 36_1_2 T54. St. Peter, Barbados: Global Sustainable Energy Consultants LTD.

———. 2018. 'Paving the Way for Renewable Electricity in Barbados'. Stakeholder Meeting presented at the Barbados Renewable Energy Association, Bridgetown, Barbados.

https://brea.bb/wp-content/uploads/2017/07/Paving-the-Way-for-Renewable-Electricity-in-Barbados-BREA-Presentation.pdf.

Holder, Nikolai, Marilaine Mota-Meira, Jens Born, and Sarah L. Sutrina. 2020. 'Bio-Methane Production via Anaerobic Co-Digestion by Optimizing the Mixing Ratios of River Tamarind (Leucaena Leucocephala) and Dolphin Fish (Coryphaena Hippurus) Offal'. *Processes* 8 (8): 934. https://doi.org/10.3390/pr8080934.

Hoyte, Dario. 2016. 'Shore-to-Ship Power for Cruise Ships on "100% Renewables" in the Bridgetown Port, Barbados.' Master's Thesis. RNEM6010 – Energy Economics. The University of the West Indies - Cave Hill Campus- Faculty of Science and Technology: Centre for Resource Management and Environmental Studies (C.E.R.M.E.S).

IADB. 2009a. 'SUPPORT FOR SUSTAINABLE ENERGY FRAMEWORK FOR BARBADOS (SEFB) I'. (BA-L1022). Barbados, Bridgetown: Inter-American Development Bank. http://idbdocs.iadb.org/wsdocs/getdocument.aspx?docnum=35425963.

———. 2009b. 'SUSTAINABLE ENERGY FRAMEWORK FOR BARBADOS'. Plan of Operation. (BA-T1007). Barbados, Bridgetown: Inter-American Development Bank. http://idbdocs.iadb.org/wsdocs/getdocument.aspx?docnum=1866829.

IEA. 2021. 'Wind – Renewables 2020 – Analysis'. Paris: International Energy Agency. https://www.iea.org/reports/renewables-2020/wind.

Ihlemann, Maren, Iasonas Kouveliotis-Lysikatos, Jiangyi Huang, Joseph Dillon, Ciara O'Dwyer, Topi Rasku, Manuel Marin, Kris Poncelet, and Juha Kiviluoma. 2021. 'SpineOpt: A Flexible Open-Source Energy System Modelling Framework'. *Submitted for Review*.

IMF. 2023. 'FIRST REVIEWS UNDER THE EXTENDED FUND FACILITY ARRANGEMENT AND UNDER THE RESILIENCE AND SUSTAINABILITY FACILITY, REQUESTS FOR MODIFICATION OF PERFORMANCE CRITERIA AND REFORM MEASURES, AND REPHASING OF ACCESS UNDER THE RESILIENCE AND SUSTAINABILITY FACILITY—PRESS RELEASE; STAFF REPORT; AND STATEMENT BY THE EXECUTIVE DIRECTOR FOR BARBADOS'. IMF Country Report 23/241. Washington, D.C: International Monetary Fund.

Indexmundi. 2021. 'Barbados - Arable Land (Hectares)'. Environmental Indicators: Land-use. Barbados - Arable Land. 1 January 2021. https://www.indexmundi.com/facts/barbados/indicator/AG.LND.ARBL.HA.

IRENA. 2016. 'Barbados Energy Roadmap'. Energy Roadmap. United Arab Emirates: International Renewable Energy Agency.

———. 2019a. 'Innovation Landscape Brief: Artificial Intelligence and Big Dat'. Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_AI_Big_Data_2019.pdf.

———. 2019b. 'Renewable Power Generation Costs in 2018'. Abu Dhabi: International Renewable Energy Agency. https://www.enerjiportali.com/wp-content/uploads/2019/05/IRENA_2018_Power_Costs_2019.pdf.

———. 2020a. 'Costs: Data, Research and Resources on Renewable Energy Costs.' /Costs. June 2020. https://www.irena.org/costs.

———. 2020b. 'Innovative Operation of Pumped Hydropower Storage - Innovation Landscape Brief'. Innovation Landscape Brief. Abu Dhabi: International Renewable Energy Agency.

Janke, Leandro, Athaydes Leite, Marcell Nikolausz, Thomas Schmidt, Jan Liebetrau, Michael Nelles, and Walter Stinner. 2015. 'Biogas Production from Sugarcane Waste: Assessment on Kinetic Challenges for Process Designing'. *International Journal of Molecular Sciences* 16 (9): 20685–703. https://doi.org/10.3390/ijms160920685.

Jebaraj, S., and S. Iniyan. 2006. 'A Review of Energy Models'. *Renewable and Sustainable Energy Reviews* 10 (4): 281–311. https://doi.org/10.1016/j.rser.2004.09.004.

Khoodaruth, A., V. Oree, M. K. Elahee, and Woodrow W. Clark. 2017. 'Exploring Options for a 100% Renewable Energy System in Mauritius by 2050'. *Utilities Policy* 44 (February):38–49. https://doi.org/10.1016/j.jup.2016.12.001.

Kim, Namsuk. 2020. *How Long Will It Take for LDCs and SIDS to Recover from the Impacts of COVID-19?* United Nations, Department of Economic and Social Affairs.

Kojonsaari, Anna-Riikka, and Jenny Palm. 2021. 'Distributed Energy Systems and Energy Communities Under Negotiation'. *Technology and Economics of Smart Grids and Sustainable Energy* 6 (1): 17. https://doi.org/10.1007/s40866-021-00116-9.

Korberg, Andrei David, Iva Ridjan Skov, and Brian Vad Mathiesen. 2020. 'The Role of Biogas and Biogas-Derived Fuels in a 100% Renewable Energy System in Denmark'. *Energy* 199 (May):117426. https://doi.org/10.1016/j.energy.2020.117426.

Kotzur, Leander, Lars Nolting, Maximilian Hoffmann, Theresa Groß, Andreas Smolenko, Jan Priesmann, Henrik Büsing, Robin Beer, Felix Kullmann, and Bismark Singh. 2021. 'A Modeler's Guide to Handle Complexity in Energy Systems Optimization'. *Advances in Applied Energy* 4:100063.

Kuang, Yonghong, Yongjun Zhang, Bin Zhou, Canbing Li, Yijia Cao, Lijuan Li, and Long Zeng. 2016. 'A Review of Renewable Energy Utilization in Islands'. *Renewable and Sustainable Energy Reviews* 59 (June):504–13. https://doi.org/10.1016/j.rser.2016.01.014.

Lauer, Markus, Uwe Leprich, and Daniela Thrän. 2020. 'Economic Assessment of Flexible Power Generation from Biogas Plants in Germany's Future Electricity System'. *Renewable Energy* 146:1471–85.

Leal Filho, Walter, Johannes M. Lütz, David N. Sattler, and Patrick D. Nunn. 2020. 'Coronavirus: COVID-19 Transmission in Pacific Small Island Developing States'. *International Journal of Environmental Research and Public Health* 17 (15): 5409.

Lin, Bo-Jhih, and Wei-Hsin Chen. 2015. 'Sugarcane Bagasse Pyrolysis in a Carbon Dioxide Atmosphere with Conventional and Microwave-Assisted Heating'. *Frontiers in Energy Research* 3 (February):1–9. https://doi.org/10.3389/fenrg.2015.00004.

López, Pérez, and I Berdellans. 2002. 'Cuba'. *Centro de Gestión de La Información y Desarrollo de La Energía* (blog). 2002. https://www.un.org/esa/sustdev/publications/energy_indicators/chapter4.pdf.

Lopion, Peter, Peter Markewitz, Martin Robinius, and Detlef Stolten. 2018. 'A Review of Current Challenges and Trends in Energy Systems Modeling'. *Renewable and Sustainable Energy Reviews* 96 (November):156–66. https://doi.org/10.1016/j.rser.2018.07.045.

Lorde, Troy, Brian Francis, and Lisa Drakes. 2011. 'Tourism Services Exports and Economic Growth in Barbados'. *The International Trade Journal* 25 (2): 205–32. https://doi.org/10.1080/08853908.2011.554788.

Lorde, Troy, Kimberly Waithe, and Brian Francis. 2010. 'The Importance of Electrical Energy for Economic Growth in Barbados'. *Energy Economics* 32 (6): 1411–20. https://doi.org/10.1016/j.eneco.2010.05.011.

Lund, H., and B. V. Mathiesen. 2009. 'Energy System Analysis of 100% Renewable Energy Systems—The Case of Denmark in Years 2030 and 2050'. *Energy*, 4th Dubrovnik Conference, 34 (5): 524–31. https://doi.org/10.1016/j.energy.2008.04.003.

Maïzi, Nadia, Vincent Mazauric, Edi Assoumou, Stéphanie Bouckaert, Vincent Krakowski, Xiang Li, and Pengbo Wang. 2018. 'Maximizing Intermittency in 100% Renewable and Reliable Power Systems: A Holistic Approach Applied to Reunion Island in 2030'. *Applied Energy*, Transformative Innovations for a Sustainable Future – Part III, 227 (October):332–41. https://doi.org/10.1016/j.apenergy.2017.08.058.

Manish, S., Indu R. Pillai, and Rangan Banerjee. 2006. 'Sustainability Analysis of Renewables for Climate Change Mitigation'. *Energy for Sustainable Development* 10 (4): 25–36.

Martínez-Gordón, R., G. Morales-España, J. Sijm, and A. P. C. Faaij. 2021. 'A Review of the Role of Spatial Resolution in Energy Systems Modelling: Lessons Learned and Applicability to the North Sea Region'. *Renewable and Sustainable Energy Reviews* 141 (May):110857. https://doi.org/10.1016/j.rser.2021.110857.

Maruf, Md Nasimul Islam. 2021. 'Open Model-Based Analysis of a 100% Renewable and Sector-Coupled Energy System–The Case of Germany in 2050'. *Applied Energy* 288:116618. https://doi.org/10.1016/j.apenergy.2021.116618.

Masson, Malaika, and Luis Perez. 2021. 'Electrifying the Caribbean: Plugging in Electric Vehicles'. *Energía Para El Futuro* (blog). 16 August 2021. https://blogs.iadb.org/energia/en/electrifying-the-caribbean-plugging-in-electric-vehicles/.

Mathiesen, Brian Vad, Henrik Lund, and Kenneth Karlsson. 2011. ‘100% Renewable Energy Systems, Climate Mitigation and Economic Growth’. *Applied Energy*, The 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, held in Dubrovnik September/October 2009, 88 (2): 488–501. https://doi.org/10.1016/j.apenergy.2010.03.001.

Meschede, Henning, Michael Child, and Christian Breyer. 2018. ‘Assessment of Sustainable Energy System Configuration for a Small Canary Island in 2030’. *Energy Conversion and Management* 165:363–72. https://doi.org/10.1016/j.enconman.2018.03.061.

Metwally, Amany A., Rasha M. Abo-bakr, and Dalia S. Ahmed. 2023. ‘Sustainable Methane Energy from Bagasse Treated via Bokashi Technology: Comparative between Neural Network and Mathematical Modeling’. *Clean Technologies and Environmental Policy*, October. https://doi.org/10.1007/s10098-023-02601-4.

Miller, Mark. 2020. ‘Data: Fossil Fuel Mix for Barbados’. The Barbados National Energy Information System (NEIS). Bridgetown, Barbados: The Division of Telecommunications: The Research Department.

Morrison, Robbie. 2018. ‘Energy System Modeling: Public Transparency, Scientific Reproducibility, and Open Development’. *Energy Strategy Reviews* 20 (April):49–63. https://doi.org/10.1016/j.esr.2017.12.010.

Mott MacDonald. 2021. ‘Integrated Resource & Resiliency Plan for Barbados’. Draft Report. Brighton: Inter-American Development Bank.

Müller, Berit, Francesco Gardumi, and Ludwig Hülk. 2018. ‘Comprehensive Representation of Models for Energy System Analyses: Insights from the Energy Modelling Platform for Europe (EMP-E) 2017’. *Energy Strategy Reviews* 21 (August):82–87. https://doi.org/10.1016/j.esr.2018.03.006.

Nagel, Janet. 2018. *Optimization of Energy Supply Systems*. Springer.

National Renewable Energy Laboratory. 2020. ‘WEB Aruba N.V (Generator)’. Energy Transitions Initiative (U.S. Department of Energy). *Aruba Energy Snapshot* (blog). June 2020. https://www.nrel.gov/docs/fy20osti/76635.pdf.

Niles, Keron. 2013. ‘Energy Aid in Caribbean and Pacific Small Island Developing States (SIDS)’. PhD Thesis, University of Otago.

Niles, Keron, and Bob Lloyd. 2013. ‘Small Island Developing States (SIDS) & Energy Aid: Impacts on the Energy Sector in the Caribbean and Pacific’. *Energy for Sustainable Development* 17 (5): 521–30. https://doi.org/10.1016/j.esd.2013.07.004.

NPC. 2021. ‘About « National Petroleum Corporation’. About Us: Importation of Natural Gas. 2021. http://www.npc.bb/about/.

NREL. 1997. ‘Dollars from Sense: The Economic Benefits of Renewable Energy’. DOE/GO--10097-261, 538051. Washington, D.C: National Renewable Energy Laboratory. https://doi.org/10.2172/538051.

OAS. 2016. ‘Cuba Electricity Industry: Current Situation and Perspectives’. *Documents* (blog). 16 April 2016. https://www.oas.org/dsd/reia/Documents/geocaraibes/cuba_presentation.pdf.

oemof. 2021. ‘Libraries’. Software Libraries. *Oemof: A Modular Open Source Framework to Model Energy Supply Systems* (blog). 2021. https://oemof.org/libraries/.

Owen, Nick A., Oliver R. Inderwildi, and David A. King. 2010. ‘The Status of Conventional World Oil Reserves—Hype or Cause for Concern?’ *Energy Policy* 38 (8): 4743–49. https://doi.org/10.1016/j.enpol.2010.02.026.

Papathanassiou, Stavros A., and Nikos G. Boulaxis. 2006. ‘Power Limitations and Energy Yield Evaluation for Wind Farms Operating in Island Systems’. *Renewable Energy* 31 (4): 457–79. https://doi.org/10.1016/j.renene.2005.04.002.

Pelling, M, and J Uitto. 2001. ‘Small Island Developing States: Natural Disaster Vulnerability and Global Change’. *Global Environmental Change Part B: Environmental Hazards* 3 (2): 49–62. https://doi.org/10.1016/S1464-2867(01)00018-3.

Perez, Yannick, and Francisco Javier Ramos Real. 2008. ‘How to Make a European Integrated Market in Small and Isolated Electricity Systems? The Case of the Canary Islands’. *Energy Policy*, Transition towards Sustainable Energy Systems, 36 (11): 4159–67. https://doi.org/10.1016/j.enpol.2008.05.019.

Perlack, Bob, and William Hinds. 2001. ‘Evaluation Of Renewable Energy Incentives: The Barbados Solar Water Heating Experience’, January.

Pfeifer, Antun, Pero Prebeg, and Neven Duić. 2020. ‘Challenges and Opportunities of Zero Emission Shipping in Smart Islands: A Study of Zero Emission Ferry Lines’. *eTransportation* 3 (February):100048. https://doi.org/10.1016/j.etran.2020.100048.

Pfenninger, Stefan, and Iain Staffell. 2016. ‘Long-Term Patterns of European PV Output Using 30 Years of Validated Hourly Reanalysis and Satellite Data’. *Energy* 114 (November):1251–65. https://doi.org/10.1016/j.energy.2016.08.060.

Pitorac, Livia, Kaspar Vereide, and Leif Lia. 2020. ‘Technical Review of Existing Norwegian Pumped Storage Plants’. *Energies* 13 (18): 4918. https://doi.org/10.3390/en13184918.

Prina, Matteo Giacomo, Giampaolo Manzolini, David Moser, Benedetto Nastasi, and Wolfram Sparber. 2020. ‘Classification and Challenges of Bottom-up Energy System Models - A Review’. *Renewable and Sustainable Energy Reviews* 129 (September):109917. https://doi.org/10.1016/j.rser.2020.109917.

PyPSA Developers. 2021. ‘Optimal Power Flow — PyPSA 0.18.0 Documentation’. PyPSA Read the Docs. Optimal Power Flow. 2021. https://pypsa.readthedocs.io/en/latest/optimal_power_flow.html.

Ramos-Real, Francisco J., Josue Barrera-Santana, Alfredo Ramírez-Díaz, and Yannick Perez. 2018. ‘Interconnecting Isolated Electrical Systems. The Case of Canary Islands’. *Energy Strategy Reviews* 22 (November):37–46. https://doi.org/10.1016/j.esr.2018.08.004.

Ratnam, Kamala Sarojini, K. Palanisamy, and Guangya Yang. 2020. ‘Future Low-Inertia Power Systems: Requirements, Issues, and Solutions - A Review’. *Renewable and Sustainable Energy Reviews* 124 (May):109773. https://doi.org/10.1016/j.rser.2020.109773.

Research Department. 2020. ‘Energy Bulletin 2020 – Energy.Gov.Bb’. Energy Bulletin JANUARY-DECEMBER 2020. JANUARY - DECEMBER 2020. Energy Division: Research Department. https://energy.gov.bb/download/energy-bulletin-2020/.

Ringkjøb, Hans-Kristian, Peter M. Haugan, and Ida Marie Solbrekke. 2018. ‘A Review of Modelling Tools for Energy and Electricity Systems with Large Shares of Variable Renewables’. *Renewable and Sustainable Energy Reviews* 96 (November):440–59. https://doi.org/10.1016/j.rser.2018.08.002.

Rogers, Tom. 2017. ‘A Desktop Study into the Wind Resource in Barbados’. Bridgetown, Barbados: The University of the West Indies Cave Hill Campus.

Schipfer, F., E. Mäki, U. Schmieder, N. Lange, T. Schildhauer, C. Hennig, and D. Thrän. 2022. ‘Status of and Expectations for Flexible Bioenergy to Support Resource Efficiency and to Accelerate the Energy Transition’. *Renewable and Sustainable Energy Reviews* 158 (April):112094. https://doi.org/10.1016/j.rser.2022.112094.

Scruggs, Gregory R., and Thomas E. Bassett. 2013. ‘Coastal Zone Management: The Barbados Model’. *Land Lines*, 1–7.

Selosse, Sandrine, Sabine Garabedian, Olivia Ricci, and Nadia Maïzi. 2018. ‘The Renewable Energy Revolution of Reunion Island’. *Renewable and Sustainable Energy Reviews* 89 (June):99–105. https://doi.org/10.1016/j.rser.2018.03.013.

Sigrist, Lukas, Enrique Lobato, Francisco M. Echavarren, Ignacio Egido, and Luis Rouco. 2016. *Island Power Systems*. CRC Press.

Singer, Stephan, Jean-Philippe Denruyter, and Deniz Yener. 2017. ‘The Energy Report: 100 % Renewable Energy by 2050’. In , 379–83. https://doi.org/10.1007/978-3-319-45659-1_40.

Staffell, Iain, and Stefan Pfenninger. 2018. ‘The Increasing Impact of Weather on Electricity Supply and Demand’. *Energy* 145 (February):65–78. https://doi.org/10.1016/j.energy.2017.12.051.

Stantec. 2016. ‘The Assessment of the Potential for the Development of a Pump Storage System in Barbados’. Bridgetown, Barbados: Stantec Consulting Caribbean Ltd.

Surroop, Dinesh, Pravesh Raghoo, and Zumar M. A. Bundhoo. 2018. ‘Comparison of Energy Systems in Small Island Developing States’. *Utilities Policy* 54 (October):46–54. https://doi.org/10.1016/j.jup.2018.07.006.

Tesar, Joseph. 2019. ‘“Bio-Digestion: Benefits to Barbados.”’ Annual conference, Bridgetown, Barbados. https://www.youtube.com/watch?v=GcAsLdhT9ek.

Teske, Sven. 2019. *Achieving the Paris Climate Agreement Goals : Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5°C and +2°C*. Springer Nature. https://library.oapen.org/handle/20.500.12657/22899.

Thompson, Terrell. 2021. 'Improving the Anaerobic Co-Digestion of Pelagic Sargassum and Food Waste into Biogas and a Bio-Fertilizer Using Hydrothermal Pre-Treatment: Concept to Application in the Caribbean'. PhD Thesis, Auckland, New Zealand: The University of Auckland.

Thompson, Terrell M., Pedram Ramin, Isuru Udugama, Brent R. Young, Krist V. Gernaey, and Saeid Baroutian. 2021. 'Techno-Economic and Environmental Impact Assessment of Biogas Production and Fertilizer Recovery from Pelagic Sargassum: A Biorefinery Concept for Barbados'. *Energy Conversion and Management* 245 (October):114605. https://doi.org/10.1016/j.enconman.2021.114605.

Torabi, Roham, Alvaro Gomes, Diogo Lobo, and Fernando Morgado-Dias. 2020. 'Modelling Demand Flexibility and Energy Storage to Support Increased Penetration of Renewable Energy Resources on Porto Santo'. *Greenhouse Gases: Science and Technology* 10 (6): 1118–32. https://doi.org/10.1002/ghg.2005.

Trommler, Marcus, Tino Barchmann, Martin Dotzauer, and Antje Cieleit. 2017. 'Can Biogas Plants Contribute to Lower the Demand for Power Grid Expansion?' *Chemical Engineering & Technology* 40 (2): 359–66. https://doi.org/10.1002/ceat.201600230.

Ulbig, Andreas, Theodor S. Borsche, and Göran Andersson. 2014. 'Impact of Low Rotational Inertia on Power System Stability and Operation'. *IFAC Proceedings Volumes*, 19th IFAC World Congress, 47 (3): 7290–97. https://doi.org/10.3182/20140824-6-ZA-1003.02615.

UN Environment Programme, and REN21 Secretariat. 2020. 'Renewables 2020 Global Status Report'. 978-3-948393-00–7. Paris: REN21. https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf.

United Nations. 2021. 'World Economic Situation and Prospects 2020'. United Nations: Department of Economic and Social Affairs. https://doi.org/10.18356/9789210054980c010.

———. 2023. 'What Is the Kyoto Protocol? | UNFCCC'. 3 March 2023. https://unfccc.int/kyoto_protocol.

University of Iowa. 2024. 'Capacity of Transmission Lines'. University Educational Files. 10 April 2024. https://www.imse.iastate.edu/files/2021/03/EnergyProject_Capacity_of_Transmission_Lines.pdf.

UN-OHRLIS, United Nations. 2021. 'COVID-19 in SIDS | Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States'. COVID-19 Funding for Small Island Developing States. March 2021. https://www.un.org/ohrlls/content/covid-19-sids.

UN-OHRLLS, United Nations. 2011. 'Small Island Developing States Small Islands Big(Ger) Stakes'. New York, NY: Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States.

———. 2017. 'Small Island Developing States in Numbers'. New York, NY: Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States.

Urban, FRMJ, R. M. J. Benders, and H. C. Moll. 2007. 'Modelling Energy Systems for Developing Countries'. *Energy Policy* 35 (6): 3473–82.

Vazquez, L., Y. Majanne, M. Castro, J. Luukkanen, O. Hohmeyer, M. Vilaragut, and D. Diaz. 2018. 'Energy System Planning towards Renewable Power System: Energy Matrix Change in Cuba by 2030'. *IFAC-PapersOnLine*, 10th IFAC Symposium on Control of Power and Energy Systems CPES 2018, 51 (28): 522–27. https://doi.org/10.1016/j.ifacol.2018.11.756.

Walker, Gordon, and Patrick Devine-Wright. 2008. 'Community Renewable Energy: What Should It Mean?' *Energy Policy* 36 (2): 497–500. https://doi.org/10.1016/j.enpol.2007.10.019.

Wang, Haifeng, Xiaoli Mao, and Dan Rutherford. 2015. 'Costs and Benefits of Shore Power at the Port of Shenzhen'. International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/ICCT-WCtr_ShorePower_201512a.pdf.

Wärtsilä. 2020. 'Wärtsilä Power Plant to Support Reliability of Electricity System and Renewable Capacity in Barbados'. Wartsila.Com. 23 January 2020.

https://www.wartsila.com/media/news/23-01-2020-wartsila-power-plant-to-support-reliability-of-electricity-system-and-renewable-capacity-in-barbados-2622917.

Watson, Daren, Yekini Binnie, Keith Duncan, and Jean-Francois Dorville. 2017. ‘Photurgen: The Open Source Software for the Analysis and Design of Hybrid Solar Wind Energy Systems in the Caribbean Region: A Brief Introduction to Its Development Policy’. *Energy Reports* 3 (November):61–69. https://doi.org/10.1016/j.egyr.2017.03.001.

Wingenbach, Clemens, Simon Hilpert, and Stephan Günther. 2017. ‘Entwicklung Eines Open Source Energie-Modells Für Schleswig-Holstein (openMod. Sh)’. *Flensburg. Retrieved from Zentrum Für Nachhaltige Energiesysteme (ZNES) Website: Https://Www. Uniflensburg. de/Fileadmin/Content/Abteilungen/Industrial/Dokumente/Downloads/Veroeffentlichungen/Forschungsergebnisse/Openmodsh-Endbericht-1. Pdf*.

Wolf, Franziska, Dinesh Surroop, Anirudh Singh, and Walter Leal. 2016. ‘Energy Access and Security Strategies in Small Island Developing States’. *Energy Policy* 98 (November):663–73. https://doi.org/10.1016/j.enpol.2016.04.020.

World Population Review. 2021. ‘Barbados Population 2021 (Demographics, Maps, Graphs)’. World Population Review. 2021. https://worldpopulationreview.com/countries/barbados-population.

Worldometer. 2023. ‘Barbados Population (2023) - Worldometer’. 2023. https://www.worldometers.info/world-population/barbados-population/.

Wyllie, Jamalia O.Y., Emmanuel A. Essah, and Eng L. Ofetotse. 2018. ‘Barriers of Solar Energy Uptake and the Potential for Mitigation Solutions in Barbados’. *Renewable and Sustainable Energy Reviews* 91 (August):935–49. https://doi.org/10.1016/j.rser.2018.04.100.