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Final Report (RD)

Barbados Clean Energy Storage and EV Policy

Prepared by:

aceler

Prepared for:

MESBE

PRIDE AND INDUSTRY

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Ministry, Energy Division, Barbados

Abstract:

Barbados can achieve BNEP clean energy plan by 2030 if technologies of storage and vehicle to grid (V2G) are procured along with renewables procurements. Contained in this report are details surrounding strategy and use cases of storage technologies and V2G technologies to facilitate 100 percent clean energy of Barbados power sector by 2030 according to BNEP. There is an opportunity to set a policy around storage and V2G technologies based on the guidance in this report.

Reviews:

- 1st Stakeholder Presentation - Overview of study
- Review Meetings with Ministry and BLPC
- Comments from BLPC
- Comments from Ministry
- 2nd Stakeholder Meeting – Overview of the draft report
- Comments from FTC
- Comments from BREA
- Comments from Developer
- Comments from MESBE

1. Executive Summary

The recently concluded 26th UN Climate Change Conference of the Parties (COP26), held in Glasgow, demonstrated the enormous difficulties that much of the world faces in plotting a path to instituting large-scale clean energy goals. As other nations grapple with a variety of hurdles – ranging from political to economic to feasibility – the Government of Barbados continues to move ahead with its National Energy Policy (BNEP) of transitioning to 100% renewable energy by 2030. With its domestic interests substantially aligned, the Government of Barbados is unhindered in planning a credible path to implementation of its renewable energy goals by 2030. For the island-state, the transformation of its power grid is not only technically feasible but is also expected to deliver significant economic and strategic benefits, including large-scale investment and job creation as well as independence from external energy suppliers.

This is not to underestimate the extent of the transformation that is required to overhaul an electricity grid that remains over 90% reliant on fossil fuels as of 2021. Rather, it is an affirmation that both the necessary technological maturity as well as the depth of capital markets are now in place to facilitate an orderly transition to 100% renewable energy in Barbados by 2030. Ultimately, the success of this transition will be dependent on ensuring that the correct policies are enacted to ensure that the grid of the future remains reliable and resilient, even as it adheres to the BNEP goals.

This report, prepared by Acelerex and powered by its proprietary software platforms, outlines the policies, investments, and approaches which will be necessary to ensure a successful transition for Barbados' national power grid. The key to credibly ensuring such a transition will be a large-scale investment in both stationary storage and V2G services, which will help ensure that the power grid remains reliable and resilient as the island-state's energy mix rapidly shifts towards solar and wind generation. Storage and V2G technologies – assisted by record capital flow from the private sector – are now ready for widespread deployment.

This study recommends policies that are geared towards opening up such investments to the private sector, allowing the island-state to benefit from a substantial inflow of foreign capital as well as reducing the financial burden of the BNEP on public finances. As an added benefit, foreign stationary storage and V2G services companies – which are likely to be almost exclusively from friendly North American and European nations – will bring with them both jobs as well as technical knowledge to the Barbados workforce. From the perspective of North American and European companies – many of whom have been extremely well-capitalized through the course of 2021's record year for funding such technologies – the opportunity to participate in the world's most aggressive transition to 100% renewable energy is likely to provide enhanced strategic interest in pursuing such investments. For such investment to occur, it is recommended to ensure free and fair access to the private sector.

The centrality of required investments in stationary storage and V2G technologies is observable in a simple simulation of how a typical daily supply-demand balance in Barbados is expected to evolve over the coming decade. First, the increased installed capacity of renewables – driven especially by the plentiful supply of solar resources in Barbados – lowers the net demand required to be supplied by BLPC. In some cases (during peak hours) the net demand that should be satisfied by the dispatchable resources becomes non-positive, creating a surplus of power that is expected to expand dramatically as more solar capacity is installed between now and 2030. This phenomenon is generally referred to as the "duck curve," a name that originated in California, a region that experiences similar solar conditions to Barbados.

The Barbados "duck curve" with net demand to be supplied by dispatchable resources for future years is illustrated in Figure 1. The conditions of the "duck curve" require ramping up of power to stabilize the grid and also cause curtailment risks. If such conditions are not addressed, they not only create resiliency issues but also can result in substantial economic losses for power generators. These conditions are, however, suitably addressed by investments in stationary storage and V2G technologies, which then act as a natural balancing mechanism by providing a demand outlet for the excess supply of solar power during peak periods.

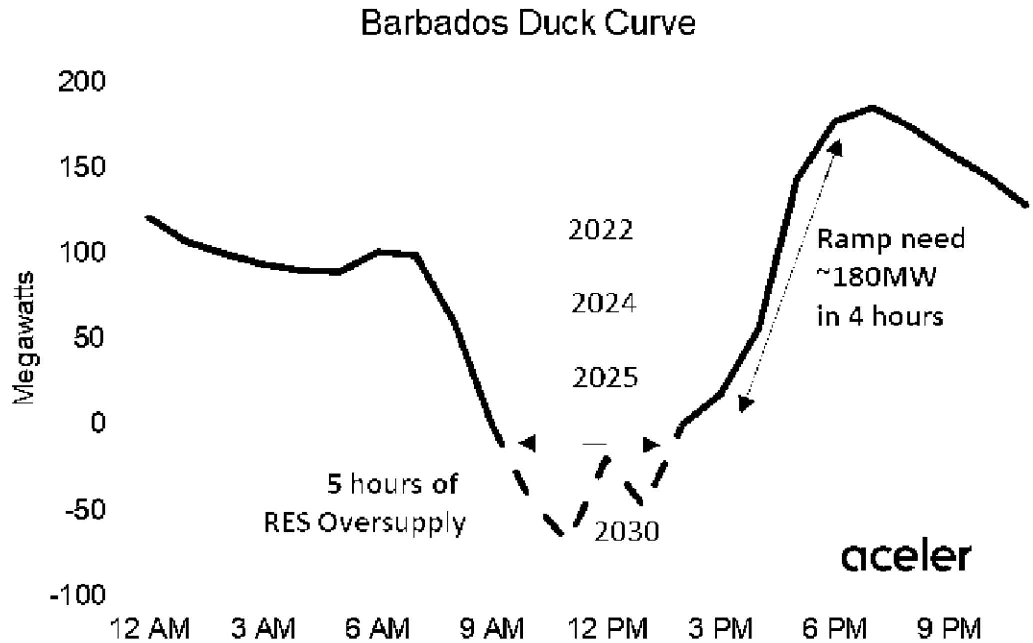

Figure 1: Barbados Duck Curve (2022-2030)

Source: BLPC, Acelerex Chart: Acelerex

The duck was named "Francine" in reference to PS Blackman, Ministry, Energy Division, IRRP 2020-2021 Study

The Barbados power systems are simulated for the years between 2022 and 2030, demonstrating the role that energy storage systems and V2G can play in ensuring grid resilience.

In order to implement such an investment program, this study provides specific recommendations to support the growth of cost-effective storage and V2G deployment on the Barbados grid. These policy and regulatory recommendations seek to maximize the system benefits of energy storage via long-term ratepayer cost reductions, increased grid resilience and maintaining grid reliability, and decreased GHG emissions. The recommendations can unlock the clean energy integration potential of energy storage on the Barbados electric grid. Implementation of these policy and regulatory recommendations should ensure that Barbados not only establishes itself as a pioneer but also a success in the global energy transition: delivering jobs, investment, technical know-how, and energy security to the island-state while maintaining a 100% renewable-powered power grid that is cost-effective, reliable and resilient.

For the implementation of Energy Storage resources along with the renewable resources to achieve 100% decarbonization, a market with storage policies and regulation is required which drives the investments and monetizes the services provided by Energy Storage. As discussed in detail in this report, Energy Storage can provide multiple services providing reliability and resiliency to the power grid along with intermittent resources. The services provided by Energy Storage and the required size for the Barbados grid are evaluated based on how the services are controlled. The services covered in-detailed are the Services Controlled by Central Dispatcher, Services Controlled by Local Dispatcher, Stacked Services, and Virtual Power Plants (VPP).

Individual analysis of energy storage services for Barbados' future grid requirements shows a requirement of 690 MW of energy storage with a range of duration requirements based on the use case. These services include energy arbitrage, distribution hosting capacity, spinning reserves, black start, solar firming and ramping, EVs, peak shaving, frequency regulation, demand response, renewable curtailment reduction, and energy with long duration in absence of solar generation. The storage power capacity evaluated by each service increases every year due to the increased renewable integration to the grid. The power capacity and duration requirements by individual services are shown in Figure 2 indicating the maximum capacity that would be required to provide that service at a time.

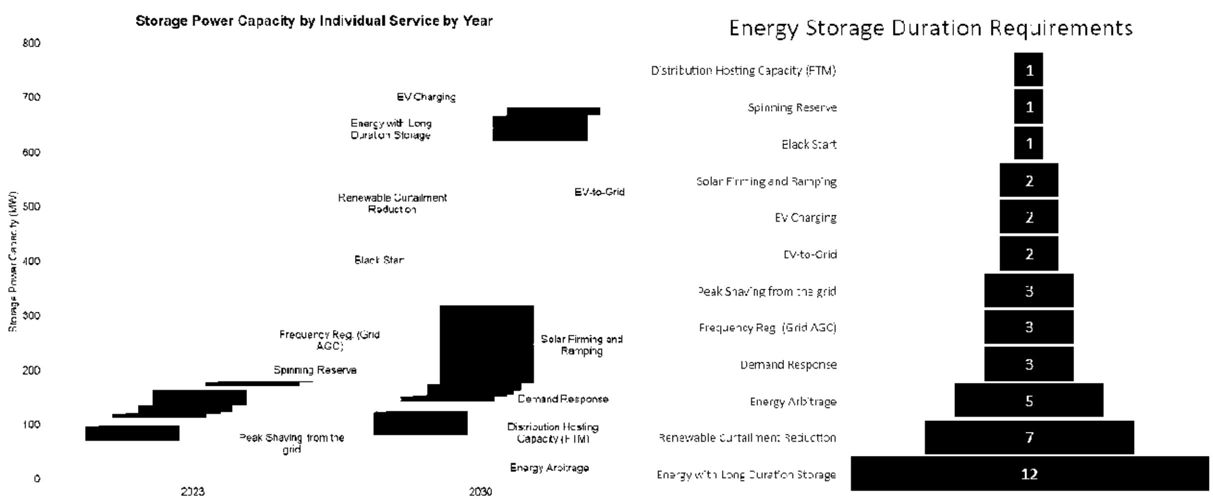

Figure 2: Storage Power Capacity by Individual Service in 2023 and 2030

Chart: Acelerex

All these services won't be required at the same time and not each of them would require the same amount of power capacity and energy capacity. The beauty of energy storage devices is that they can be dispatched for multiple services at the same time where their power and energy capacity is allocated separately for each service that is required at a particular time interval. These services based on the local or central control can be economically driven or reliability has driven for the grid. Such dispatch of multiple services is described in this report as Stacked Services.

The dispatch of Stacked Services requires policy implementation and defined market products for each service that Energy Storage can provide and can get monetized. With the Stacked Service, the overall requirement of storage capacity reduces drastically as shown in Figure 3 as many of these services can share the storage power and energy capacity.

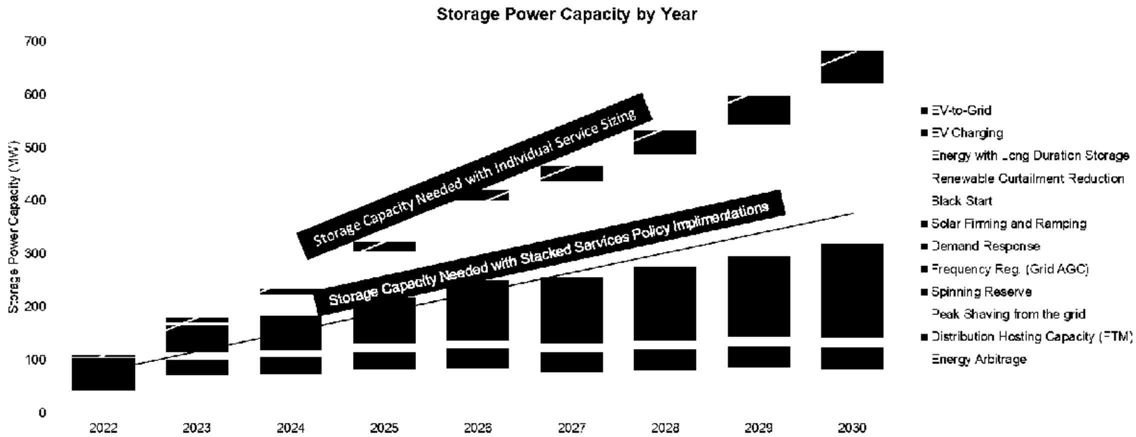

Figure 3 Energy Storage Power Capacity by Service by Year

Chart: Acelerex

The stacked services approach in which the energy storage systems can provide more than one service during the day is a technically viable approach to lower the total capacity requirement of storage in the power system. The coincidence of two services required at the same time is lower for some services such as peak shaving and renewable curtailment reduction. While the storage units are required for renewable curtailment reduction service generally during the noon, the peak shaving service is required around the evening in Barbados. Therefore, the same physical storage unit can indeed provide these services; therefore, increasing the capacity factor of the investments. The stacked services for a typical day in Barbados in 2025 and 2030 are illustrated in Figure 4. While the long-duration storage service and the spinning reserve service allocations are constant over time, other services that can be called upon by the central control room can be stacked during the day.

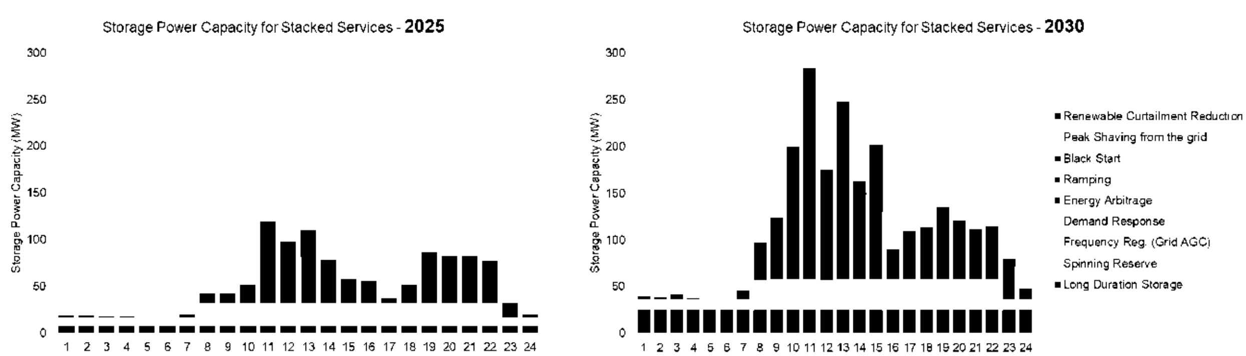

Figure 4: Storage Power Capacity for Stacked Services in 2025 and 2030

Chart: Acelerex

With the development of multiple small-scale or medium-scale energy storage resources, renewable resources, EVs across the Barbados grid, a Virtual Power Plant (VPP) could be implemented which allows a cloud-based control and dispatch of the resources based on the grid reliability and resiliency requirements. For the reliability and resiliency of the Barbados power grid, a policy should be implemented that tracks the net demand and pays the dispatchable resources that keep themselves available for the duration when renewable generation is at its peak to avoid any curtailments and grid instability.

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2. Energy Storage Policy Recommendations

The study provides a suite of recommendations to support the growth of cost-effective storage and V2G deployment on the Barbados grid. These recommendations are expected to yield new energy storage technologies on the Barbados grid by 2030. These policy recommendations seek to maximize the system benefits of energy storage via long-term ratepayer cost reductions, increased grid resilience and maintaining grid reliability, and decreased GHG emissions. The recommendations can unlock the clean energy integration potential of energy storage on the Barbados electric grid. The energy storage policy recommendations should also be supported with a regulatory framework for energy storage. The regulatory framework should aim to create an equal level playing field for energy storage.

- It needs to provide clear rules and responsibilities concerning the technical modalities and the financial conditions of energy storage.
- It must address barriers preventing the integration of storage into markets.
- It should be technology-neutral, ensuring fair competition between different technological solutions.
- It should ensure fair and equal access to electricity storage services independent of the size and location of the storage in the supply chain.
- It should ensure medium-term predictability in the investment and financial conditions (taxes, fees, etc.), enabling favorable conditions for all kinds of storage.
- It could help improve the business/economic model for energy storage.

To enable the short term and large scale deployment of storage in Barbados a number of actions could be undertaken:

- Developing and assessing visions for the role of storage in integrating variable renewable sources, optimizing the use of generation and energy network capacities, providing services to the electricity system, and promoting distributed generation to improve energy efficiency and reduce CO_2 emissions, as envisaged by the indicative targets for 2030.
- Synergies could be made by a common approach to storage for electricity systems and storage for transport (upcoming Electric vehicles, Plug-in hybrid vehicles);
- Supporting the development of consumer-based energy storage services linked with local RES production, smart meters, and smart local grids that ensure financial benefits for the consumers.
- Support for storage within the regulatory adjustments to enable storage to facilitate the progress towards the 100% renewable target.
- Mapping storage potential and demonstration via pilot projects.
- All different forms of energy storage could be supported by feed-in-tariff support providing they contribute towards the energy targets (technology-neutral; target-oriented).

2.1 Pilot Projects

Pilot projects are needed to support a learning curve of all storage services. This group of pilot projects will assess options to integrate energy storage systems and evaluate the associated benefits and costs. The goal of pilot projects is to understand how the use of storage can provide stacked services when managed in grid operations. The pilots will help understand the return of investment on resiliency-related investments and advanced customer offerings. Pilots for these new technologies enhance the understanding of technology, integration, customer behavior, and societal benefits, as well as help, increased adoption, and usage of electric transportation and clean energy. The pilot projects are categorized under distributed energy storage, virtual power plant, and vehicle-to-grid technologies.

Distributed Energy Storage Pilot Projects: Behind-the-meter energy storage solutions will be at customer scale assets (1-100kW). The pilot program tests the need for and benefits of integrated storage, how to determine optimal locations for storage. It will evaluate storage operating strategies coordinated with other distributed energy resource assets. The pilot will also evaluate the impact on and support system reliability measures.

Virtual Power Plant Pilot Projects: This group of pilot projects will explore a variety of virtual power plant (VPP) options along with resultant benefits and costs. The VPP pilot consists of distributed energy resources, energy storage systems, and electric vehicle chargers. It can test the use and control of VPP infrastructure as an integrated asset to the utility.

Vehicle-to-Grid Pilot Projects: This group of pilot projects will evaluate the integration, benefits, and costs of EV charging infrastructure. The pilots will cover home EV charging stations, public charging infrastructure (third-party and utility-owned), and vehicle-to-grid (V2G) capable technological assets. The projects will test the need for and benefits of integrated deployment, hardware, software, and grid integration of EV charging infrastructure. During the pilot, customer behavior can be analyzed and the impact on greater adoption of EVs can be evaluated.

Rate Structures Pilot Program: The rate structures for the participants of pilot projects can be different than the usual customers. For example, evaluation of time of use rates for charging behavior impacts or testing pricing influence on use EV charging options is applicable. Testing of pricing models relative to grid support, load management, and reliability can be applied to energy storage system pilots.

2.2 Advanced Dispatch Software

The integration of energy storage systems into the power grid can be simple or complicated based on the goal of the integration. To utilize the most benefit out of each storage capacity integrated into the grid, a stacked services approach should be adopted. The capability of storage devices to provide stacked services simultaneously or over time is the technological advancement of these devices; however, digitalization of the utility and hence the advanced communication infrastructure is needed to achieve better efficiency. The collection of data from various resources in almost real-time is critical to creating a dispatch schedule for a storage system. Both centralized and distributed dispatch for stacked services for energy storage will be necessary to maintain grid reliability and resiliency.

2.3 Ramping

The high penetration of renewable energy sources in transmission and distribution networks has challenged the stability of the power grid due to the intermittent nature of the sources. An energy storage system can be considered as a fast-acting backup source to accommodate higher penetration of RES. When rapid changes to renewable output occur, it’s difficult for traditional generation schemes to deal with. That’s why PV sites should implement ramp rate control at the site level. Cloud movement was traditionally considered unavoidable, and no requirement existed to limit the ramp back to active power setpoint after cloud departure. But Barbados is moving to a new era where this will no longer be the case. However, there's a big problem with a typical ramp rate control. It actually deoptimizes solar sites. Therefore, the site output will be lower than ideal and an overall loss in potential solar generation. The energy storage solution can be a PV energy optimizer. It allows a site to behave like a firm, dispatchable energy source. It can be used to eliminate the variability induced by scattered clouds and allow for a smooth ramp when shutting the plant down at the end of the day.

2.3.1.1 The ratio of storage to solar procurements

For the new solar capacity procurements, placing a requirement to purchase a certain amount of storage for each incremental purchase of solar is recommended to ensure grid stability. The required storage capacity should be estimated from the ramp rate of the solar plant to ensure that the power output does not change significantly. Solar output firming can help improve grid conditions due to the increased installed capacity of renewables.

2.4 Solar & Storage Hosting capacity

The hosting capacity analysis can help utility, policymakers better understand the impact of adding new distributed photovoltaic or energy storage systems to the electrical distribution system. The hosting capacity analysis considers the thresholds at which new systems will trigger upgrades or changes to the electrical distribution system and evaluates the cost of different options for expanding the hosting capacity. The hosting capacity is the amount of solar and/or storage that can be added to the distribution system before control changes or system upgrades are required to safely and reliably integrate additional systems.

2.5 Time-of-use rates

Time-of-use (TOU) retail energy rates price electricity differently by the time of day, thereby communicating to consumers the costs of supplying electricity throughout the day. TOU rates are part of a broader movement to modernize demand-side loads. Two types of TOU rates can be implemented one for behind-the-meter applications and one for V2G services and these rates can be made to be dynamic to mitigate congestion on the grid.

2.6 Storage Feed-in-Tariff Program

The main challenge for energy storage development is economic. The economic and business case varies from case to case, depending, among other things, on where the storage is needed: generation, transmission, distribution, or customer level. When developing Feed-in-Tariffs (FIT), policy makers need to evaluate how FITs interact with existing or proposed policies - both how FITs might create synergies with other policies and how their interaction may create unintended consequences.

Two basic installations of storage systems exist, i.e. storage installed as a separate unit or as part of a hybrid system. The installation in a hybrid system does not necessarily mean that producing RES units (wind or photovoltaic or any other power plant) are physically installed at the same location as the storage unit. It could be just a conceptual combination of these two plants where each unit has its grid connection but is operated as a single hybrid system. To size, a FIT program for storage is to determine the amount of solar installed under FIT and then determine the net load ramping and intermittency impacts of that solar and determine the amount of storage that is required to limit ramping according to the future grid code ramping requirement.

2.7 Grid Code

Energy Storage should not be seen as a stand-alone technology. It will certainly compete and /or complement other ways to improve the grid flexibility. Placing the definition of storage services and the ramping requirement for hybrid systems in the grid code are recommended for Barbados. Then procurement of storage systems as needed in amounts is required by system studies going forward based on the amounts of renewables procured each year.

2.8 Procurement of capacity for wear & tear

For procurement of storage, the easiest approach is the procure capacity and dispatch rights and wear and tear amounts on an annual or quarterly basis. Then pay for the capacity on a monthly basis upon demonstration of availability to provide the capacity and be dispatchable and provide the wear and tear. The supplier provides fixed and variable O&M costs that are additionally priced at the monthly rate. The bidders will bid for the monthly rate of the capacity. The bidder should guarantee the efficiency and the efficiency should be used in the evaluation of the bids. A more detailed version of the competitive procurement and licensing can be found in the report titled "Competitive Procurement and Licence Process" [1].

2.9 Stacked Services

The potential to develop new and innovative business models: energy storage studies in both Europe and the US demonstrate that the provision of a single service (e.g. kWh) was not sufficient to make the storage scheme cost-effective. One single service will probably not be the most cost-optimal solution. A mix of all services is needed, tailored for each region and system architecture.

2.9.1.1 Centralized & Distributed Stacked Services

The peak increase issue can be solved where energy storage is available at different levels of the Electrical System: centralized energy storage as a reserve; distributed storage in the form of demand management and demand response systems and for grid support when aggregated and operated as a VPP. These different locations in the power system will involve different stakeholders and will have an impact on the type of services to be provided. Each location will provide a specific share of deregulated and regulated income streams. Different energy storage systems will have to be considered (centralized and distributed) and specific business models will have to be identified.

3. Introduction

The Barbados Energy Storage Study is conducted to quantify the indicative size and timing of potential distributed energy storage projects that can add maximum benefit to the ratepayers in Barbados. The energy storage study is conducted with transparent assumptions and stakeholder-driven processes, providing analysis regarding the potential value streams that energy storage can provide over the long-term period.

3.1 Flaws in Standard Market Design Create an Arbitrage Opportunity

Figure 5 (below) shows how Standard Market Design distorts the price of power during peak penetration of renewables-generated power (e.g. wind and solar). During such periods, the quoted market price for power — in part driven by production tax credits for renewables — goes to zero. Of course, the production price is not zero and the value to the customer is not zero. This flaw in Standard Market Design leads to an effective penalization of producers and transfer of economic value to the consumers. The economic penalty to producers is concentrated (e.g. a large cost is absorbed by a relatively small number of market participants) whereas the benefit to consumers is diffuse (e.g. a small gain is distributed among a large number of participants). Therefore, until now, the economic benefit to the consumer of power has gone relatively unappreciated by the market.

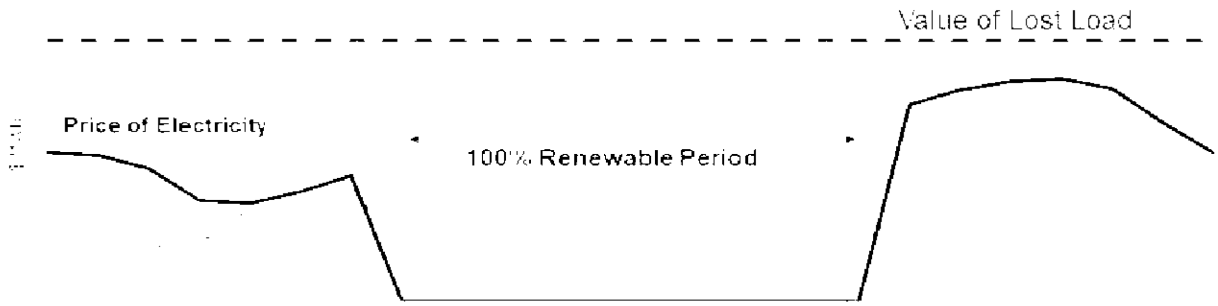


Figure 5: Market Energy Price Drops

3.2 Policy Shortcomings in Action: The “Duck Curve”

The result of this mispricing is a sizable excess supply of power during the periods of peak renewables penetration into the market. Especially for regions such as California, this coincides with the portion of the day when solar power production becomes particularly cheap and plentiful. This results in the production curve looking like a duck, with the “belly” protruding as the net load becomes increasingly negative. As net loads go negative, the risk of required curtailments creates another potential economic penalty for producers.

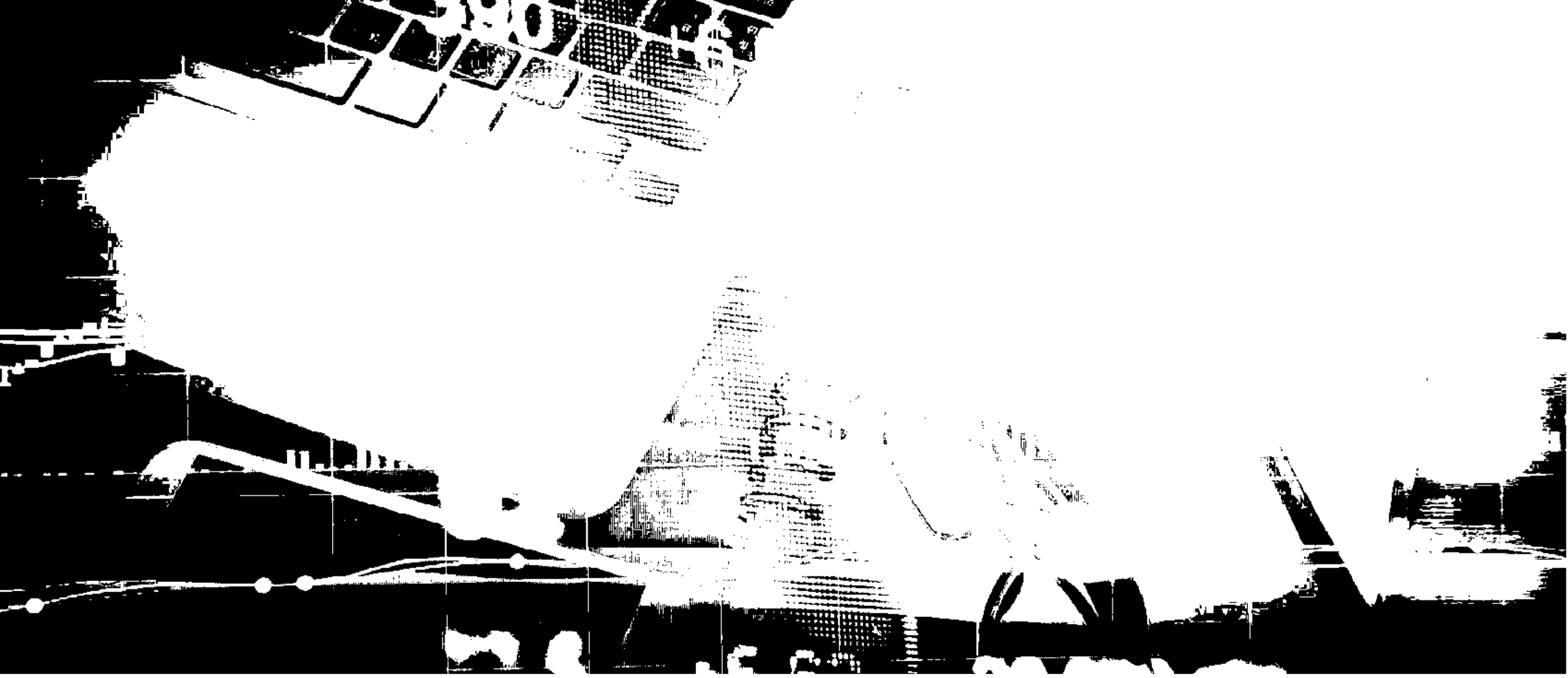
3.3 Opportunity for Private Investors in Storage and V2G Technology to Promote Resilience

The upshot of the policy shortcomings is that there is an obvious opportunity for private sector investors in storage and V2G technology to take advantage of the artificially cheap price of power to consumers during periods of peak renewables penetration. As such investments come online, they will allow consumers to seize the arbitrage opportunity created by the flaw in Standard Market Design, absorbing the excess supply of power. In the process, the private sector — both investors and consumers — will emerge as the natural medium-term mechanism for promoting grid resiliency in the United States.

The study uses a refined and updated database of data from the Integrated Resource & Resiliency Plan for Barbados [2] and EIA [3], with the addition of industry-recognized data where necessary to determine the recommended size of the energy storage deployment. For each site under evaluation, energy, power, location, and timing of distributed energy storage are determined, along with a full range stacked services benefit assessment. In addition to this, potential operational benefits, financial savings, and additional revenue opportunities are realized through the deployment of energy storage in Barbados.

Over the long term, ES systems can provide value by reducing the price paid for electricity energy consumption, reducing peak demands, avoiding the cost of transmission and distribution investments, avoiding capital investments in new capacity, increasing renewable penetration, and increasing flexibility, reliability, resiliency and for reduction of GHG and other environmental benefits.

The study is based on historical data and other assumptions of demand forecast, fuel price forecast, generator additions, and deactivations, transmission flows and constraints, and future renewable expansions.



4. Solar & Demand & Dispatch Analysis

This chapter provides the statistical and technical analysis of historical solar, demand, and dispatch data. Acelerex received the historical hourly solar generation data, hourly demand data, and hourly dispatch of all thermal generators from MESBE for this study. The solar analysis includes the up and down hourly ramping of solar generation, the expected solar generation in the future years with the increased installed capacity, and the observed outages. The demand analysis includes the annual peak, off-peak, and average demand, the upward or downward hourly ramping requirements, load duration curve, and when and how long the brownouts occur in the system. Lastly, the dispatch analysis uses the historical dispatch of thermal generators to calculate their historical ramp capabilities and their capacity factors

4.1 Historical Demand Analysis

The historical hourly demand analysis provides a comprehensive view of the electricity demand evolution in Barbados between 2017 and 2020. The demand analysis is based on two main components: statistical analysis and electricity-related technical analysis. The hourly demand of Barbados doesn't see a significant seasonality impact. A typical week demand profile is consistent throughout the year. The system observed brownout and blackouts two or three times a year in a short amount of time. A significant change in the demand curve occurred in March 2020 and kept the daily peak lower than all other historical years. The hourly demand curves per year are given in Figure 6.

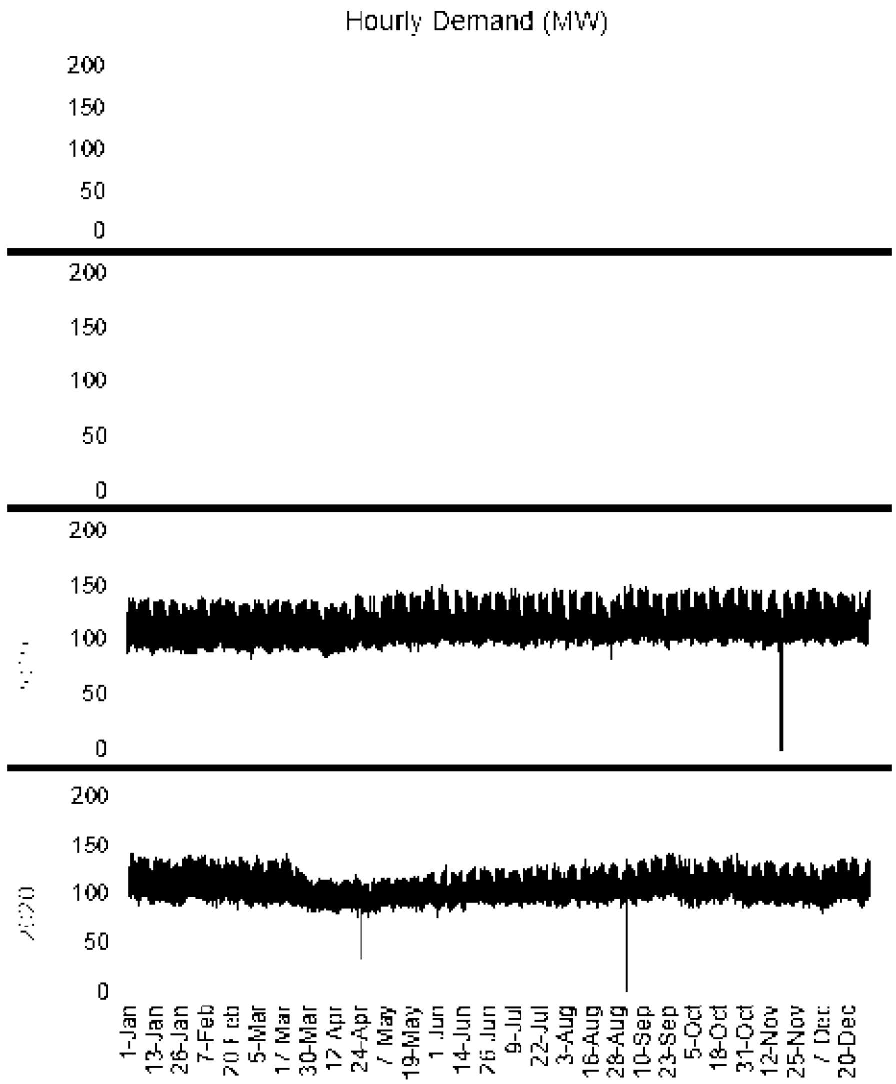


Figure 6: Hourly Demand Curve (2017-2020)

Source: BLPC, Chart: Acelerex

The peak, off-peak, average, and demand cycling are calculated using the statistical analysis and they are given in Table 1.

Table 1: Historical Demand Statistics by year

Source: BLPC

Metric	2017	2018	2019	2020
Peak (MW)	159.1	152.3	150.5	141.0
Off-peak* (MW)	83.6	77.4	81.3	76.8
Average* (MW)	118.0	117.5	116.7	107.7
Average Daily Cycling* (MW)	48	46	42	35

* Brownouts and blackouts are excluded in the calculations

The daily demand cycling is calculated as the difference between the daily peak and off-peak, and the average daily cycling is calculated by averaging the daily cycles for a year. The average daily cycling is in a downward trend since 2017 from 48MW to 35MW. One of the reasons would be the reduced load levels day and night in 2020 and 2021 due to reduced business activity resulting from COVID protocols. It would have lowered the peak without significantly impacting the base usage and hence the reduced cycling. As seen in Figure 7, the daily cycling doesn't necessarily reflect a seasonality effect but there is demand profile variance on the weekends in comparison to the weekdays. The average daily cycling is around 32.4MW on weekends versus 43.1MW on weekdays.

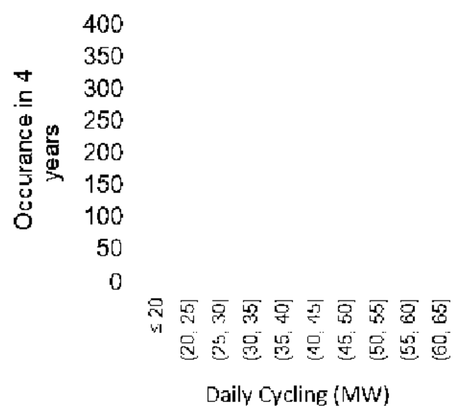


Figure 7: Daily Cycling (2017-2020)

Source: BLPC, Chart: Acelerex

The hourly demand curve for a week also shows that weekday demand profiles are similar to each other in terms of magnitude and temporal impact, but weekend profiles are similar only in time yet changes in magnitude. Sundays have generally less demand than Saturdays. Due to the significant impact of the pandemic on the electricity consumption in Barbados in 2020, the typical week by season is illustrated in 2019 to reflect the profile better in Figure 8.

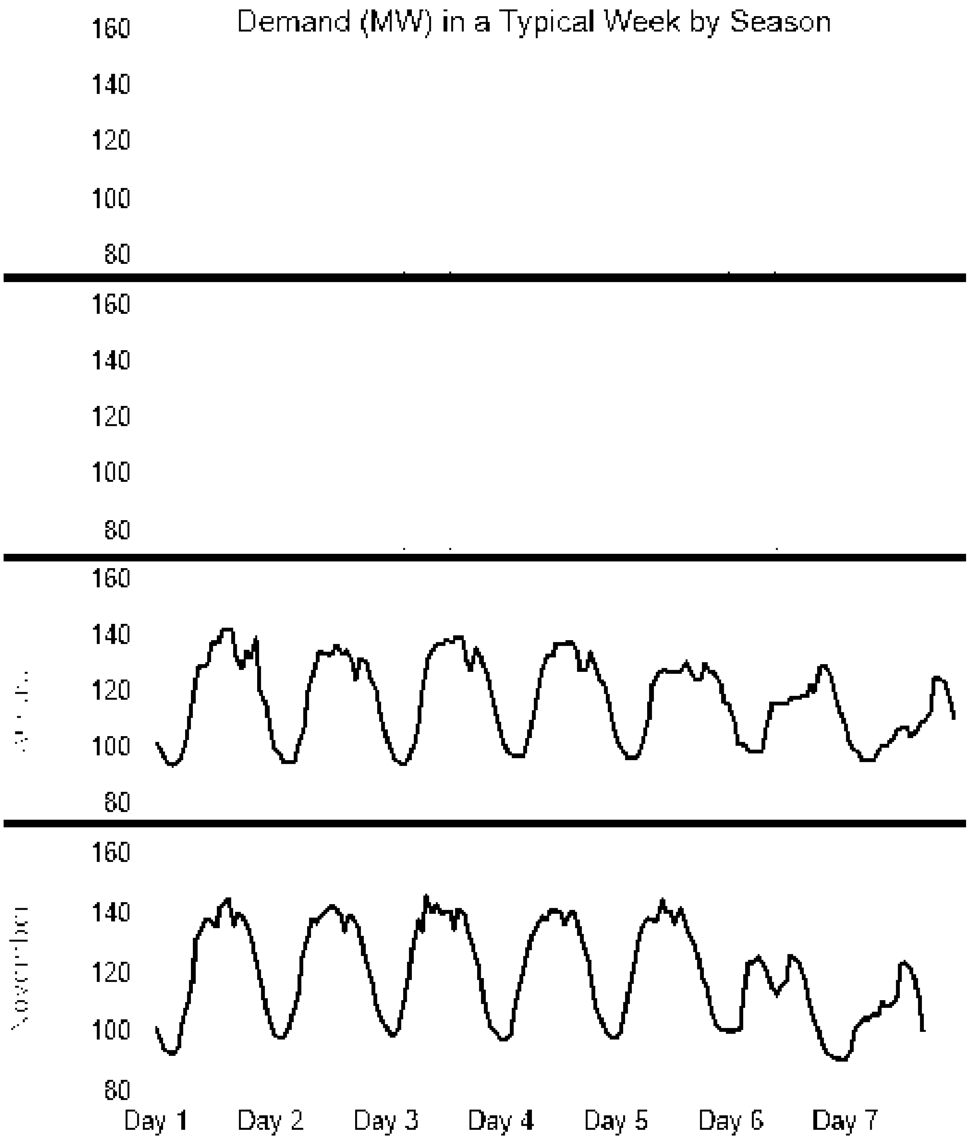


Figure 8: Typical Week Demand Curve by Season (2019)

Source: BLPC, Chart: Acelerex

4.2 Historical Solar Generation Analysis

Based on the historical hourly solar generation data received from the BLPC, statistical and technical analyses are completed. Figure 9 shows the hourly solar generation of a solar plant between 2017 and 2020 with an installed capacity of 10MW. The capacity factor of the plant is 20%, 20.6%, 21.7%, and 18.9% in 2017 through 2020 respectively. The low-capacity factor in 2020 might be related to the outage that can be observed visually in Figure 9 as well.

[redacted]

Figure 9: Solar Generation Curve (2017-2020)

Source: BLPC, Chart: Acelerex

The monthly solar capacity factor of the existing solar plant is studied and illustrated in Figure 10.

[redacted]

Figure 10: Monthly Solar Capacity Factor (2017-2020)

Source: BLPC, Chart: Acelerex

The intermittency of the solar generation in the historical data can also reveal the amount of ramping service that should be satisfied by the other generators. Therefore, the upward and downward ramping of the existing solar plant is also studied to understand the possible intermittency-related problems that Barbados may have faced in the future. The maximum up & down ramps of the existing 10 MW solar plant are given in Table 2.

Table 2: Maximum Historical Up & Down Ramps of 10MW Solar Plant

Source: BLPC

[redacted]

A possible generation dispatch scenario is also studied for a typical week in 2030 based on the solar and wind capacity additions and their possible generation profiles. The graph on the left in Figure 11 shows the possible generation dispatch without any storage deployment in 2030. While solar generation varies during the day, it is also not always similar among the days. Similarly, a possible wind generation may vary for all hours and it is possible not to have any wind generation for a couple of hours or even days. Therefore, the rest of the demand should be satisfied by the non-renewable technologies, and the required hourly ramping need may exceed 100MW/hr. However, the energy storage systems can decrease the ramping needs by providing energy after noon, while charging energy during the peak solar times; that would have been curtailed otherwise. The figure on the right in Figure 11 shows the same week with energy storage deployments. The surplus solar is stored in the storage devices every day to support the generation mix and to reduce the ramping needs from 100MW/hr to 80MW/hr. A typical week example illustrated in Figure 11 includes 154MW/4h and 50MW/3h storage systems integrated into the grid. With the higher deployment of storage devices, a further reduction in the ramping need would have been achieved.

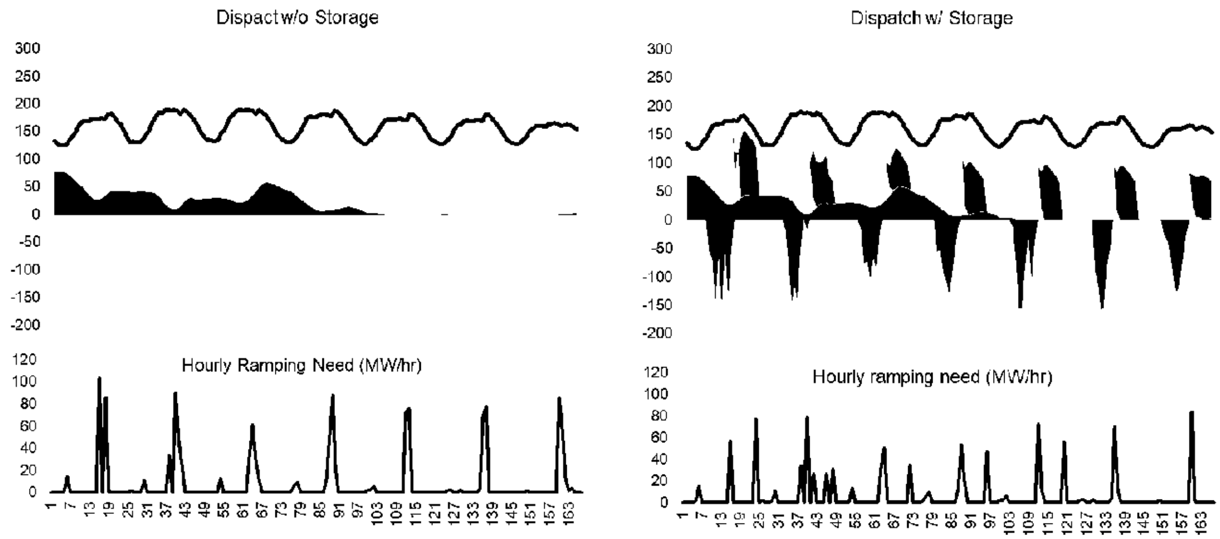


Figure 11: Ramping Needs in 2030 with and without Storage (2030)

Source: Acelerex, Chart: Acelerex

The future solar generation forecast is calculated based on the installed capacity forecast given in the Barbados IRRP. The calculation uses the hourly average generation of 4-years historical solar data as a reference with 10MW installed capacity. The identified outages/maintenance of the solar plant is excluded in the averaging process. The annual energy demand forecast is also studied together with the expected solar generation to show the solar share of the total fuel mix per year until 2030. The solar share starts with 9.2% in 2021 and increases to 45.4% in 2030.

Table 3: Solar Generation Forecast per Year (Scenario 3 in IRRP)

Source: BLPC

Metric	Solar PV Installed (MW)	Annual Solar Generation (GWh)	Annual Generation Requirement (GWh)	Solar Share in Total Mix
2021	52	93	1,020	9.2%
2022	86	155	1,038	14.9%
2023	118	212	1,064	19.9%
2024	147	264	1,089	24.3%
2025	193	347	1,124	30.8%
2026	238	428	1,149	37.2%
2027	262	471	1,188	39.6%
2028	284	510	1,278	39.9%
2029	306	550	1,309	42.0%
2030	346	622	1,368	45.4%

The impact of renewables including solar and wind on the generation mix in an hourly manner may also be significant for Barbados. During the transition to 100% clean energy, the increased installed capacity of renewables lowers the net demand for the Barbados power grid, and in some cases the net demand that should be satisfied by the non-renewable generators becomes non-positive. This phenomenon is generally referred to as the duck curve in the energy sector. For Barbados, the tracking of net demand would be critical to operating the system securely and sustainably. There might be a couple of hours per day after 2025 with renewables oversupply that implies the necessity of energy storage systems in the grid. The Barbados duck curve is illustrated in Figure 1. The net demand in this chart reflects the demand that should be covered by the non-renewable generators or storage systems.

4.3 Historical Dispatch Analysis

Based on the historical hourly generation dispatch data received from the BLPC, statistical and technical analyses are completed. The statistical analysis can reveal the maximum ramping of the unit in the upward and downward directions. It can also show the maximum generation that the unit provided to the system, and the unit's minimum stable generation limit as well. The ramp-up and down capabilities of the units, their maximum and minimum generation, and their installed capacity are given in Table 4.

Table 4: Technical Specifications of Barbados Generation Fleet (2018)

Source: BLPC

Metric	Max Ramp Up (MW/h)	Max Ramp Down (MW/h)	Maximum Generation (MWh/h)
S1	17.66	18.50	19.00
S2	15.50	19.00	19.50
D10	10.00	11.50	11.50
D11	10.00	10.00	11.00
D12	11.00	11.00	12.00
D13	11.00	12.00	12.00
D14	22.00	27.00	28.00
D15	23.50	26.00	27.00
GT02	12.50	12.50	13.00
GT03	12.20	14.00	14.00
GT04	20.00	16.50	20.00
GT05	21.40	21.40	21.40
GT06	18.00	20.60	20.60

* not modeled in Acelerex study

The capacity factors of the existing fleet in 2018 are shown in Figure 12. The capacity factor reflects how frequently the generator is being dispatched, but the metric can also be interpreted as the competitiveness of generators to generate electricity. The higher the capacity factor is the lower the cost of generating electricity and vice versa. The analysis shows that the S units and D units are generally baseload units, and the GT units are peakers. The capacity factors of the units in 2018 are illustrated in Figure 12.

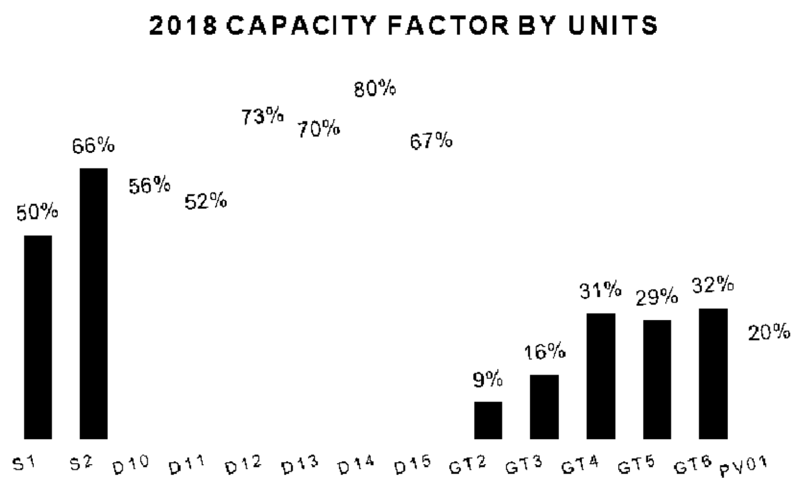
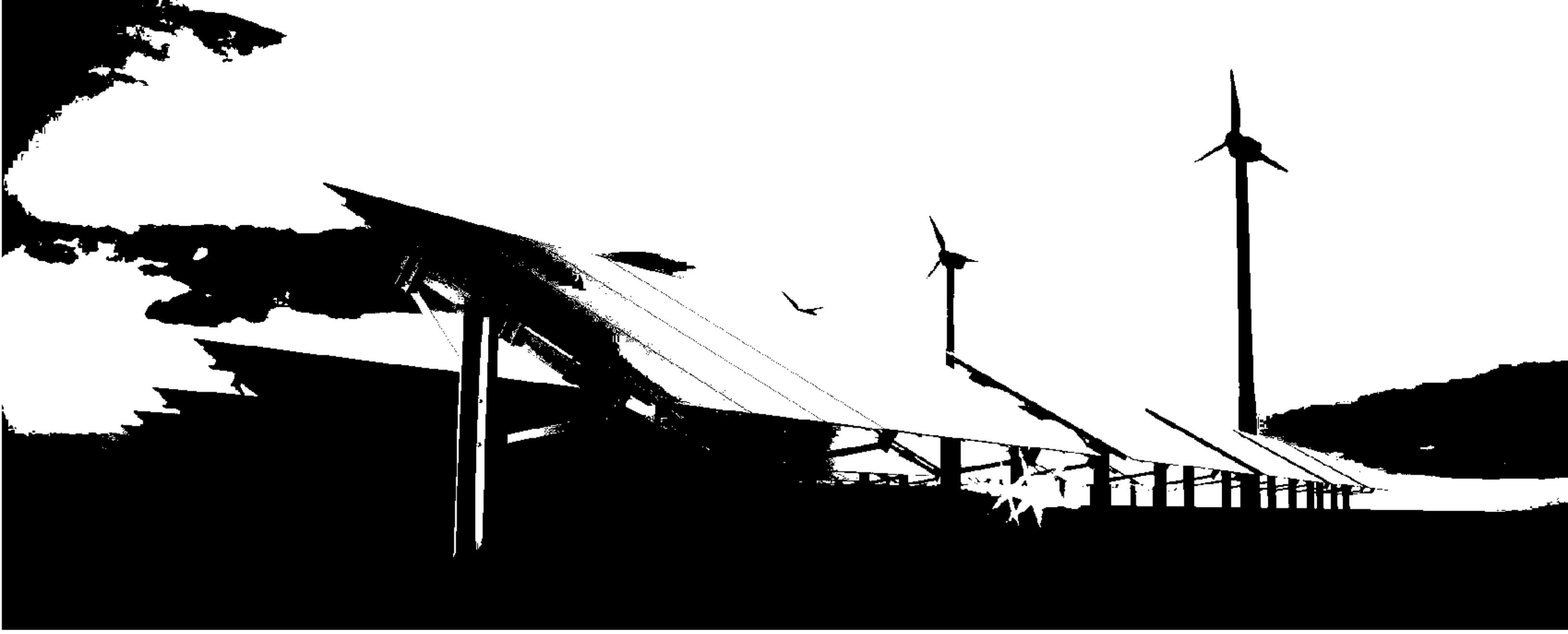


Figure 12: Capacity Factors (2018)

Source: BLPC, Chart: Acelerex



5. Renewable Firming with Ramping Conditions

Energy generation from renewable sources is a clean, environmentally friendly, and affordable solution for the sustainable future of Barbados; however, the fuel availability is different than traditional energy generation options. Solar power plants are generating electricity with direct sun exposure so they can only work during the daytime. Solar energy production can be affected by season, time of day, clouds, dust, haze, or obstructions like shadows, rain, snow, and dirt. These variations are attributable to changes in the amount of sunlight that shines onto photovoltaic panels. Shadows do impact photovoltaic panels as well. The quantity of power the photovoltaic panels can produce is directly dependent on the level of light they receive. In full, bright sunshine, solar panels receive optimal levels of light. During sunlight hours, the photovoltaic panels will produce power at their optimum capability. If there is sufficient light to cast a shadow, in spite of the clouds, the solar panels need to operate at about lower than their complete capacity. Eventually, with heavy cloud cover, solar panels will produce really little useful power.

The changing mix and natural intermittency of renewable resources threaten the grid's ability to meet supply and demand. Short-term storage can ensure that quick changes in a generation don't greatly affect the output of a solar power plant. For example, an energy storage system can be used to ride through a brief generation disruption from a passing cloud, helping the grid maintain a "firm" electrical supply that is reliable and consistent. Renewable energy generators can be mandated to meet minimum-service standards for grid stability and electricity supply. One of those standards would be renewable firming with ramping conditions.

Ramping conditions for a solar power plant for example would be limiting the solar output change between two consecutive hours with X amount of percent. The ramping allowance can be applied in both directions: upward and downward ramping. For example, a 10MW solar plant can be enforced to track its output and to follow a ±20% ramping limitation. 20% ramping limitation is applied to the maximum capacity of the solar plant; therefore, the plant is allowed to ramp up and down ±2 MW per hour.

To visualize the concept of solar firming with a 20% ramping allowance, Figure 13 shows the operational range of a solar plant with 10MW installed capacity and the real solar output for a day. The intermittency of solar output is observed at Hour 11. The solar generation reduced from 6MWh at Hour 10 to 1MWh at Hour 11, then it ramps up quickly to 9MWh at Hour 12. A similar fast ramping down is also observed between Hour 14 and Hour 15. The generation reduces from 9MWh to 4MWh which represents 5MWh ramping. The yellow border; however, shows the operational range of 20% ramping allowance for a 10MW solar plant, which corresponds to ±2MW per hour ramping limitation.

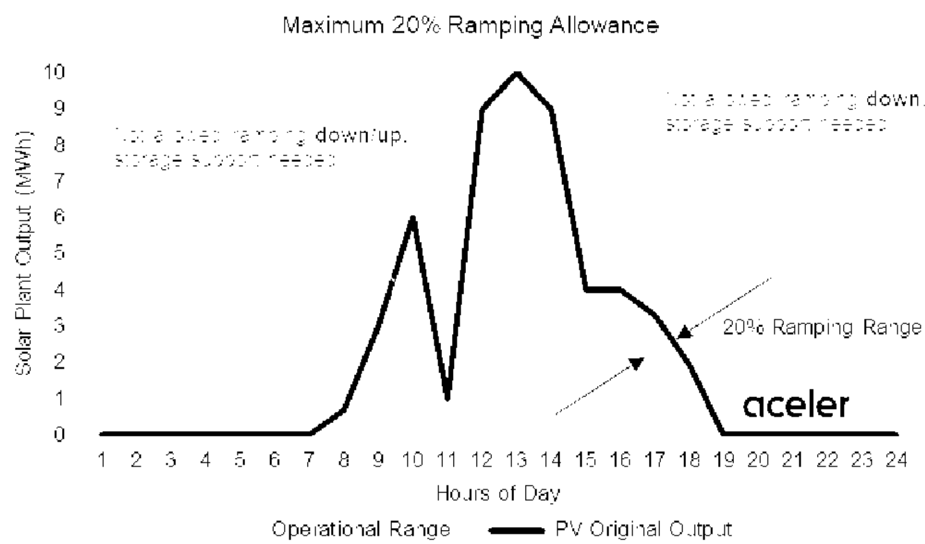


Figure 13: Real solar output and operational range with maximum 20% ramping allowance

Chart: Acelerex

Traditionally, the other generators should compensate for the intermittency; however, a storage system integration with solar can mandate the solar plant to operate in the allowed operational region so that the technical difficulty of operating the system with high ramp up/down operations are limited. An example of how a storage device can help firm the solar output is visualized in Figure 14. The green area shows the amount and time of storage support to reduce the ramping up of solar output by charging the storage. The blue area shows the amount and time of storage support to lower the ramping down of solar output by discharging the storage. Although the original solar output is shown in brown, the firmed solar output based on the 20% ramping allowance is shown in the red line in the figure below.

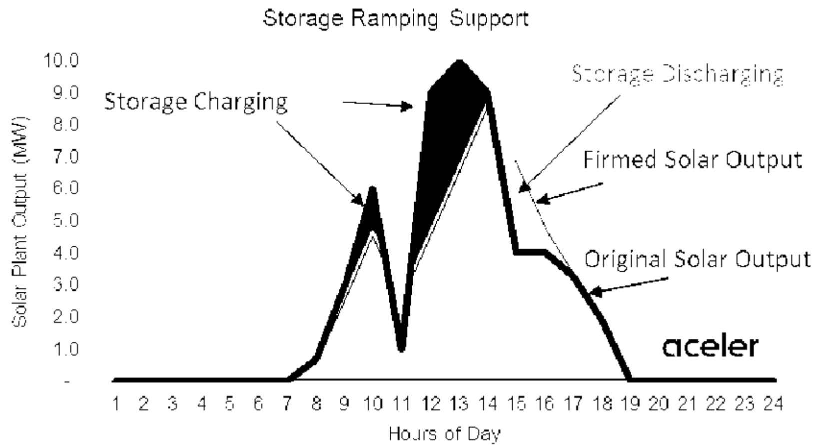


Figure 14: Storage support for renewable firming with maximum 20% ramping allowance

Chart: Acelerex

Based on the daily analysis of the solar production curve, the size of the storage system required to provide solar firming can be calculated. The size will change based on the percent ramping allowance. If 100% ramping allowance is applied, the solar doesn't require any storage capacity and all solar intermittencies will be compensated by the other resources; however, 10% ramping allowance is highly strict. Based on the real solar plant output analysis, the solar generation profile generally has 4-5 hours of ramping up starting with the sunrise and 4-5 hours of ramping down until the sunset. Therefore, a 10% ramping allowance only allows the plant to ramp up to 50% of its installed capacity until noon. Although a 10% ramping allowance would ease the operation of the grid, it may prevent the solar plants to reach their full potential. The lowest ramping allowance should be in the range of 20-30% for Barbados. Figure 15 shows the original solar output and the solar output after firming with 10% and 20% ramping allowance. The solar firming with storage indeed changes the solar output in a way that the ramping flexibility of the system can be forecasted and tracked.

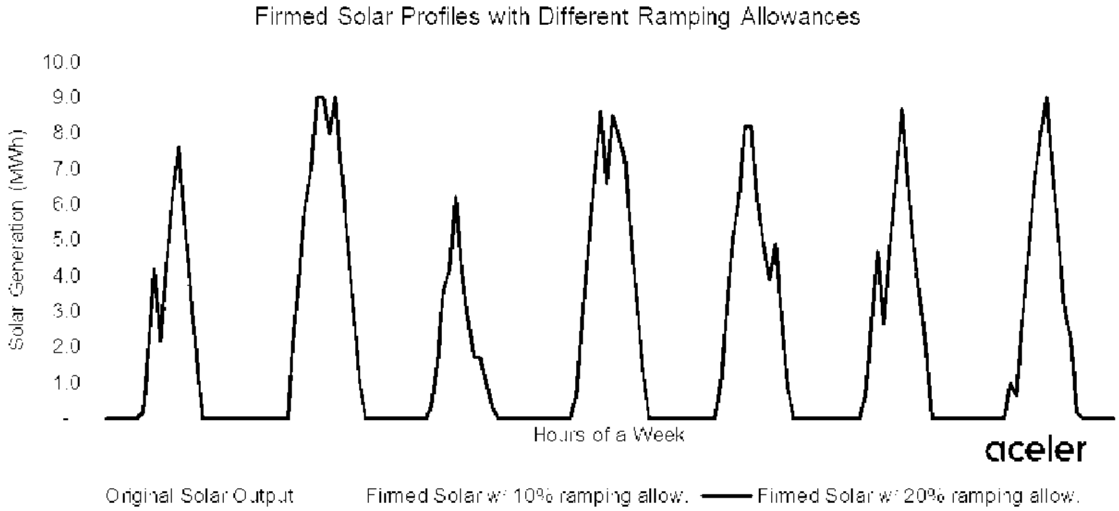


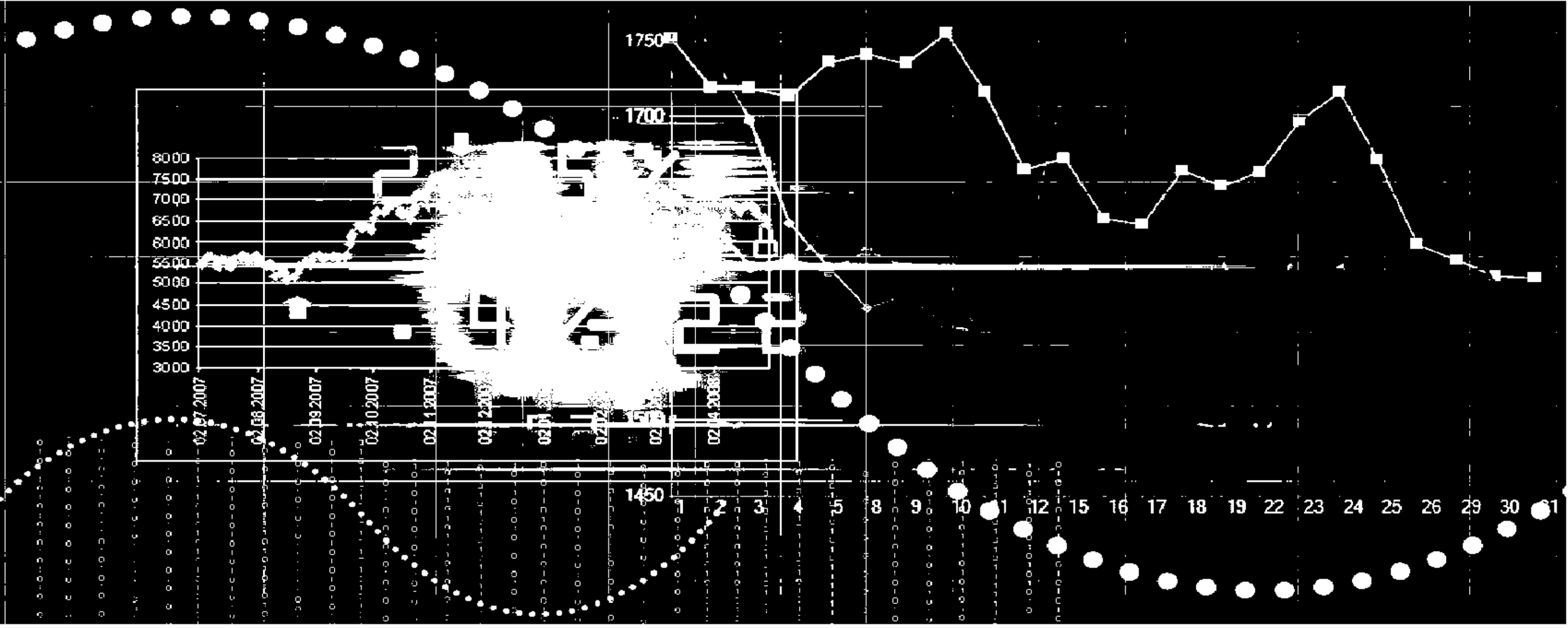
Figure 15: Firmed solar profiles with different ramping allowances

Chart: Acelerex

The above examples are related to a 20% ramping allowance, which indicates that the ramping of a solar plant cannot exceed 20% of its maximum installed capacity; however, the ramping allowance would be relaxed based on the ramping capability of the other resources in the system. Higher the ramping allowance of the solar plants, the other generation units have more responsibility for satisfying the load during the intermittencies. Table 5 summarizes the storage sizing for various ramping allowances. 20% ramping allowance requires a storage power capacity equal to 70% of solar installed capacity with at least 2.5 hours duration. For example, a 10 MW solar plant should have at least a 7MW/ 17.5MWh storage system to fulfill the ±2MW/h ramping requirement. Moreover, increase ramping allowance reduces the storage size requirement. With a 50% ramping allowance policy, solar plants will require a storage system with a power capacity of 40% of solar installed capacity with a 1.1-hour duration.

Table 5: Storage Sizing for Various Ramping Allowance

Ramping Allowance (% of installed capacity)	Storage Power Rating (MW or kW)	Storage Duration (hours)
20 %	70 % of solar installed capacity	2.5
30 %	60% of solar installed capacity	2.1
40 %	50% of solar installed capacity	1.7
50 %	40% of solar installed capacity	1.1



6. Energy Storage Services

This chapter describes the categorization of the services per control requirement, then their technical requirements and economical descriptions.

The list of stacked services identified in this study is categorized into two groups based on their control methodology. These are services by local control and services by central control. Local control implies the autonomous control of the storage system dispatch by the smart algorithms that receive only local measurements. However, the central control requires advanced algorithms at a control center where not only local measurements of the energy storage system but the current grid condition measurements are received and processed. For example, the service of grid frequency regulation requires a central control room to create a dispatch signal based on the variance on the grid frequency which is collected from several points in the grid. The list of services per control requirements is given in Table 6.

Table 6: List of Services per Control Requirements

	Services	Local Control	Central Control
1	Energy Arbitrage	X	X
2	Distribution Hosting Capacity (FTM)	X	X
3	Peak Shaving (Grid)	X	X
4	Clean Peak	X	X
5	Spinning Reserves	X	X
6	Frequency Regulation (Grid)	X	X
7	Demand Response	X	X
8	Ramping	X	X
9	Black Start	X	X
10	Long Duration Service for Solar Low Production (Grid)	X	X
11	Renewable Curtailment Reduction	X	X
12	Vehicle-to-Grid Technologies (V2G)	X	X
13	Electric Vehicle Charging (V1G)	X	X
14	Renewable Firming	X	
15	Frequency Response (Local)	X	
16	Virtual Inertia	X	
17	VPP Services	X	
18	Distribution Hosting Capacity (BTM)	X	
19	Time of Use Rate (Demand)	X	
20	Time of Use Rate (V1G, V2G)	X	
21	Local Services - Voltage Setpoint Control - Flicker Control - Power Factor Control - Manual Charge/Discharge	X	

The technical requirement defines what is needed technically to successfully use the ESS to complete this service. This might be developing a dispatch signal by the algorithms and creating a communication network between the utility and the ESS or deploying a local measurement device and implementing a smart algorithm at the ESS side to autonomously dispatch the ESS under different grid conditions. However, an economical description of the service defines how this service helps the grid to create value for the system. For example, the service of peak shaving from the grid lowers the consumption of fuel at the peaker units, it may reduce the total CO_2 emission, and it can lower the cost to load. Not all economic benefits of the service are monetized directly from the market or other structures, but they represent the value of the service. The technical and economic description of the services is given in Table 7.

Table 7: Technical and Economical Descriptions of the Stacked Services

Service	Technical Description	Economical Description
Energy Arbitrage	The dispatch signal should be provided to the ESS by the utility.	A price signal should be provided to dispatch the ESS. Otherwise, a shadow price calculation methodology should be developed to determine the value of the service.
Distribution Capacity Hosting (FTM)	Managing the distribution network capacity to accommodate the high penetration of DERs.	The impact of DERs on the distribution system can be eliminated with an optimal allocation of energy storage systems that can control the load locally within the acceptable limits even with a high level of DER contribution.
Peak Shaving (Grid)	Determine the peak hours of the day (possibly by the utility) and set the discharging amount of the ESS.	* Lowers the consumption of fuel, * lowers the CO_2 emission, * lowers the cost to load.
Spinning Reserve	Dispatch of storage in case of any contingency such as loss of a generator or a transmission/distribution line.	* Increased supply security * Increased resiliency
Frequency Reg. (Grid)	The dispatch signal should be provided to the ESS by the utility.	* Increased resiliency * Increased power quality * Insurance for an emergency, which may normally cause a local or grid brownout
Demand Response (Grid)	The dispatch signal should be provided to the ESS by the utility.	* reduced peak demand * increased resiliency * insurance for an emergency, which may normally cause load shedding
Solar Firming and Ramping	The dispatch signal should be provided to the ESS by the utility.	* power balance ramping * the reduced impact of intermittency of renewables
Black Start	Supplies the electricity needed to start a gas turbine without relying on the external transmission network.	* System resiliency
Renewable Curtailment Reduction	The dispatch signal should be provided to the ESS by the utility.	Charge the ESS by the solar and wind energy, which normally needs to be curtailed.
Energy Services with Long Duration Storage	To avoid load shedding due to lack of renewable generation. High power and high energy capacity are required to support the utility for a long period of time.	* Energy delivery to the grid * Supply security * System resiliency
EV Charging	- Charging signals are given locally when the prices are low - A signal from local control send to stop charging when prices are high - A signal from central control is sent to stop charging when peak demand is high	- Consumers can manage their charging hours based on the TOU rates applied to the EV charging bills and thereby reduce the system demand during the peak hours - Consumers can get paid if their charging is stopped during the peak hours by central control
EV-to-Grid	- Charging or discharging signal given locally based on the energy prices or TOU rates - A signal from local or central control sent to charge or discharge based on the system requirements - When connected to VPP, signals of charge-discharge based on all the grid services VPP can provide	- Consumers can manage locally the charging and also discharge providing BTM services such as TOU rate optimization, renewable shifting, and distribution capacity hosting - Consumers can get paid if they participate to support the grid and let the central control system regulate the charge and discharge - Consumers can get paid when connected to the VPP and contribute to all the services it is providing to the grid
Renewable Firming (Local)	Following the local measurement of the RES, the output is enough to avoid intermittency.	* increased reliability * reduced need on ramping service * increased supply security
Frequency Response (Local)	Following the local measurement of the frequency is enough to provide the service.	* Increased resiliency * Increased power quality * Insurance for an emergency, which may normally cause a local brownout
Virtual Inertia	Requires grid-forming inverter to provide virtual inertia. Following the local measurement of the frequency is enough to provide the service. The frequency will fall or rise much quicker if there is less inertia in the system, making this	*Provides transient response to offset Under Frequency Load Shed

Service	Technical Description	Economical Description
	technology and virtual inertia as a service more and more critical moving forward.	
Voltage Setpoint Control	Following the local measurement of the voltage at the bus is enough to keep the voltage in the allowed operational region by the grid code.	* Increased local power quality
Transient Voltage Response	Following the local measurement of the transient voltage at the bus is enough to keep the voltage in the allowed operational region by the grid code.	* Increased local power quality
Flicker Control	ESS is supported by the distribution static compensator (DSTATCOM) controlled by the use of synchronous reference frame theory (SRFT)	* Increased local power quality
Power Factor Control	Following the local measurement of the power factor at the bus is enough to keep the power factor in the allowed operational region by the grid code.	* Increased local power quality
Manual Charge/Discharge	Charge or discharge the ESS independently with no control by the utility	* bill management by TOU tariff * solar+storage integration for renewable charging * net grid demand reduction/increase

The storage capacity requirements by service can be calculated by systematic analysis of the generation fleet and demand of Barbados for each year between 2022 and 2030. The storage capacity that is needed for services that should be operated by a central dispatcher is given in Figure 16.

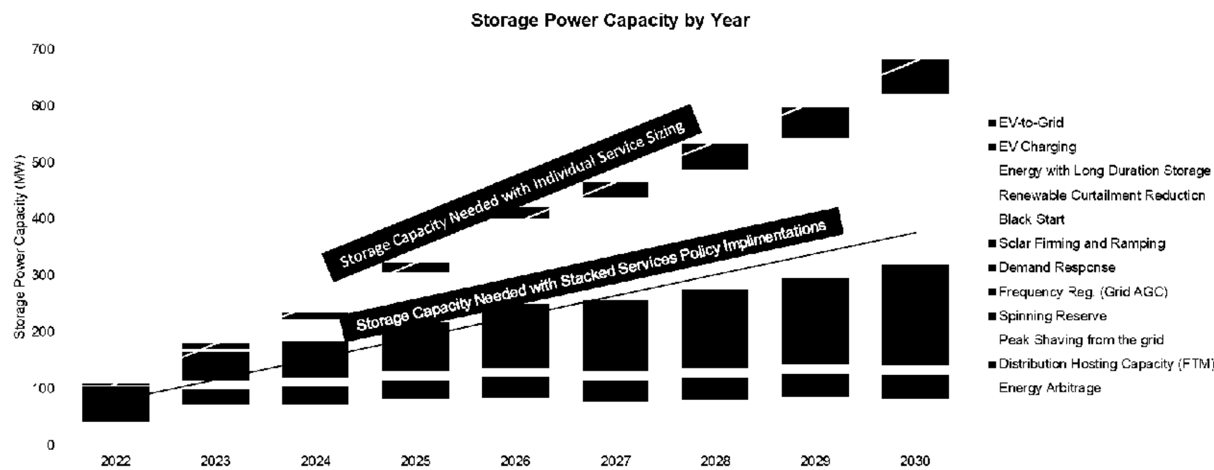


Figure 16: Storage Power Capacity by Individual Service by Year

Chart: Acelerex

When the physical energy storage system is allocated to do only one service individually, the highest increase in the capacity is observed for the service of renewable curtailment reduction. The main reason is that the energy generation capacity of solar and wind exceeds the demand; so that the surplus energy would be curtailed if not stored. The only engineering solution to reduce renewable energy curtailment is to have storage systems around the grid. Similar individual services are discussed in detail in their respective sections below.

6.1 Services Controlled by Central Dispatcher

The following sections describe each energy storage service that should be operated by the central control room. These services require advanced communication infrastructure between the control room and the physical unit on the field. To get the most benefit out of energy storage systems for the following services, non-traditional energy management system algorithms should be developed and used by the system operator. The definitions of each service are given in their respected sections below that also cover the individual storage size and duration requirement by year based on the Acelerex simulations for the Barbados generation system. However, some services may not be called and operated at all times during the day, therefore, the stacked services approach to use the same physical unit for more than one service is also discussed afterward.

6.1.1.1 Energy Arbitrage

Energy arbitrage is the ability to purchase lower-cost energy to charge the storage device and sell the stored energy during higher-cost periods. This service creates revenue for the ESS owner. Energy arbitrage is generally referred to as an application for day-ahead and real-time markets. However, it can also refer to the benefit created by reducing the total cost to load. Energy arbitrage can also reduce fossil fuel burn when lower or zero marginal costs are used to charge the energy storage and when energy storage discharges to displace fuel burn of fossil fuel peaking resources.

Methodology for Sizing: The energy arbitrage service is related to the financials rather than a technical requirement. Therefore, the hourly dispatch of storage units in the production cost results is categorized into technical or financial dispatch. Technical dispatch of storage units is related to renewable curtailment for example. The storage unit charges from the renewables which are curtailed otherwise. The financial dispatch of the storage is then categorized as the other dispatch actions that occurred at the time of no renewable oversupply. The size of the storage power capacity required for energy arbitrage service is then calculated for each day. Then the maximum daily requirement for a year is then reported in Figure 17 as the storage power capacity.

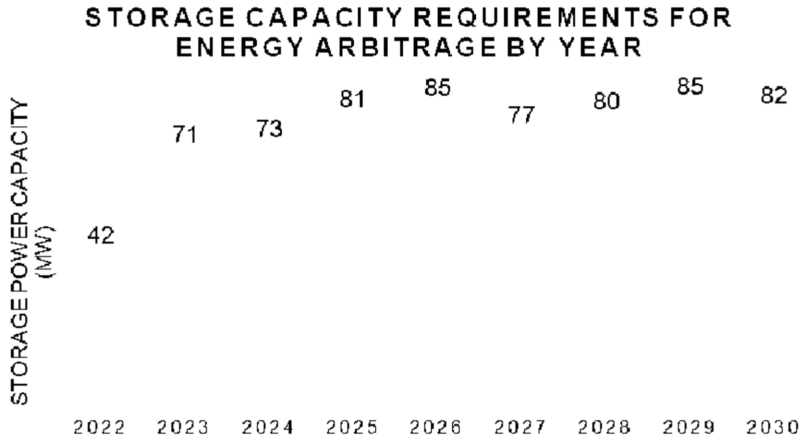


Figure 17: Power Capacity Requirements for Energy Arbitrage by year

Chart: Acelerex

The ratio between the daily energy stored for energy arbitrage and the maximum daily storage power capacity is the required duration of the storage systems. The average storage duration of all days in a year is given in Table 8.

Table 8: Storage Capacity Requirements for Energy Arbitrage by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	42	71	73	81	85	77	80	85	82
Average Storage Duration (hr)	5	6	6	6	6	5	5	5	5

6.1.1.2 Distribution Capacity Hosting (FTM)

The potential impact high penetration distributed energy resources (DER) have on distribution system performance, and ultimately the amount of DER a feeder can accommodate, depends upon many factors. Some distribution feeders can accommodate considerably higher levels of DER before operating criteria are violated, while others will have lower limits. The increased share of renewables in Barbados may lead to the question of how much DER can be accommodated before the system is pushed beyond acceptable limits. Any intermittency issues that the DERs make can be stopped with energy storage systems. The impact of DERs on the distribution system can be eliminated with an optimal allocation of energy storage systems that can control the load locally within the acceptable limits even with a high level of DER contribution.

Methodology for Sizing: The distribution capacity hosting is related to Barbados distributed solar installed capacity plans. The assumption of 105MW by 2030 based on the BNEP 2019-2030 policy target is applied for sizing the storage capacity requirements for distribution capacity hosting service. The renewable firming approach is utilized to lower the impact of distributed solar output and its intermittency on grid operations. 50% ramping allowance is applied for all distributed solar plants which corresponds to a ramping up and down limit of up to 50% of solar installed capacity. Based on the real solar output data from the Trents solar plant, a solar plant with 10MW installed capacity requires a 4MW and 1-hour energy storage system to operate within the limit of 50% ramping allowance. Based on the assumption above, the distributed solar PV capacity plan as given in Barbados IRRP is used to calculate the storage power capacity and duration for distribution hosting capacity service.

Table 9: Storage Capacity Requirements for Distribution Capacity Hosting by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Distributed Solar PV Capacity (MW)	57	69	79	86	92	97	100	103	105*
Storage Power Capacity (MW)	23	28	32	34	37	39	40	41	42
Average Storage Duration (hr)	1	1	1	1	1	1	1	1	1

* based on BNEP 2019-2030 policy target of 105 MW, referred in Barbados IRRP

6.1.1.3 Peak Shaving (Grid)

Energy storage systems can provide peak shaving by charging during off-peak load hours and discharging during peak load hours of the day. The traditional peak and off-peak hours may indeed change after a significant amount of renewable installation. Therefore, the new peak and new off-peak should be defined not by the total demand but by the net demand. The net demand is the demand that should be covered by the non-renewable generation fleet.

Methodology for Sizing: Due to the increased share of renewables in the generation fleet, the annual peak demand per year is calculated from the hourly net demand. The demand value where the shaving starts is selected to be 90% of the calculated annual peak demand per year. Therefore, the peak limit as shown in Figure 18 changes every year.

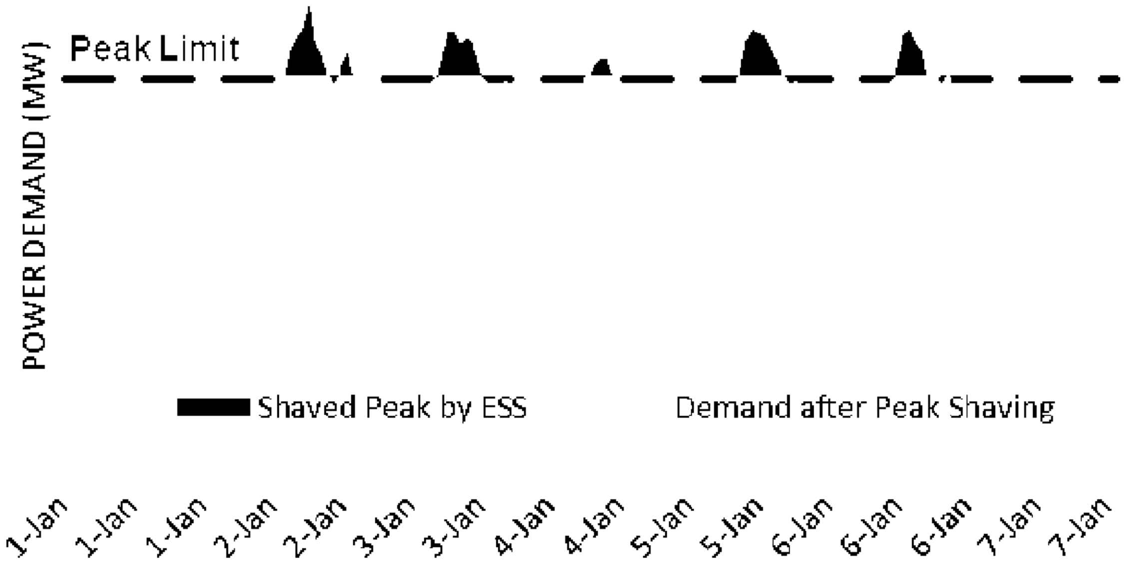


Figure 18: Illustration of Peak Shaving Service

Chart: Acelerex

The difference between the hourly net demand and the peak limit is the hourly storage power capacity required. Later, the storage power capacity requirement for peak shaving by year is calculated as the maximum of hourly storage power capacity requirements. The ratio between the daily energy stored for peak shaving and the maximum daily storage power capacity is the required duration of the storage systems. The average storage duration of all days in a year is given in Table 10.

Table 10: Storage Capacity Requirements for Peak Shaving by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	14	14	15	15	16	16	17	18	18
Average Storage Duration (hr)	4	3	3	3	3	3	3	3	3

6.1.1.4 Spinning Reserves

The energy storage systems can provide spinning reserves service, otherwise would be provided by an online conventional generator. The spinning reserve is defined as unloaded generation that is rotating in synchronism with a utility grid. However, the storage systems are technically capable of increasing their discharge capacity in less than a second and they can follow the frequency of the utility grid at all times to be in synchronism with the grid. The ESS in reserve service is not currently being used but can be quickly available in the case of an unexpected loss of generation.

Methodology for Sizing: The storage power capacity requirement for spinning reserve service is determined as the capacity of the largest online non-renewable generator in the fleet. Between 2022 and 2030, MSD Resiliency Bridge would probably be the largest unit in the Barbados fleet; hence the storage power capacity for spinning reserve service would be considered as 34 MW. However, the US ISO's allocate at most 3.8% of the peak demand for the spinning reserves as shown in Table 11.

Table 11: US Regulation and Spinning Reserve Requirements (% Peak Demand)

ISO/RTO	Regulation Reserve Requirement (Capacity Amount (MW), % of Peak Demand)	Spinning Reserve Requirement (Capacity Amount (MW), % of Peak Demand)
CAISO	RU: 320 MW (0.6%) RD: 360 MW (0.7%)	800 MW (1.6%)
ERCOT	RU: 318 MW (0.5%) RD: 295 MW (0.4%)	2,617 MW (3.8%)
SPP	RU: 470 MW (0.9%) RD: 325 MW (0.6%)	585 MW (1.1%)
MISO	425 MW (0.4%)	740 MW (0.6%)
PJM	Off-p: 525 MW (0.4%) On-p: 800 MW (0.6%)	1,505 MW (1.0%)
NYISO	217 MW (0.7%)	655 MW (2.2%)
ISO-NE	60 MW (0.3%)	900 MW (3.8%)

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The spinning reserve requirement as a percentage of the peak load increases in the US ISOs in which the renewable share is higher. Per the 100% renewable energy goal of Barbados, 4% of the peak capacity is admissible to be allocated for the possible loss of generation units. The storage units that are allocated for spinning reserve should be at standby mode following a central dispatcher signal for any contingency event. The duration of the spinning reserve service is generally less than an hour. It is so likely to replace the capacity of the lost generator within that time frame. However, the 100% renewable energy goal of Barbados also considers the retirement of several thermal generators. The traditional way of thinking of the spinning reserve to replace the lost capacity of renewables with a reserve capacity may not be relevant if the reserve capacity is also intermittent. Therefore, energy storage would play a critical role in the spinning reserve service in the upcoming years. The storage power capacity requirements for spinning reserve service by year are given in Table 12.

Table 12: Storage Capacity Requirements for Spinning Reserves by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	7	7	7	7	8	8	8	10	10
Average Storage Duration (hr)	1	1	1	1	1	1	1	1	1

The spinning reserve requirement may change based on the generation mix and available capacity of the power systems. Therefore, revisiting the sizing of storage for spinning reserve service by the dynamic simulation may be required to assess the exact need of spinning reserves over the years with the changing generation mix in Barbados.

6.1.1.5 Frequency Regulation (Grid)

Frequency regulation describes the increase, known as regulation-up, or the reduction, known as regulation-down, of power generation to maintain the system frequency at approximately 50 hertz. As defined by EPRI, regulation is the portion of a unit's unloaded capability that can be loaded, or loaded capability that can be unloaded, in response to Automatic Generation Control (AGC) signals from a central dispatcher [4]. In the case of energy storage systems, due to their capability to change their output from charging to discharging, their technical characteristic is very much suitable for providing the frequency regulation service. A frequency following signal should have been prepared and sent to the storage system. Unless otherwise the frequency regulation signal is designed and prepared for storage systems specifically, the demand-driven regulation signal may continuously call an upward or downward direction within the hour. In that case, short-duration energy storage systems may fail to deliver the service after it is fully charged or discharged.

Methodology for Sizing: Stand-alone storage systems of 5-10 MW would be ordered to always provide such service for Barbados. The storage capacity requirements for frequency regulation by year are given in Table 13. The medium duration storage such as 3 hours would serve better for this service.

Table 13: Storage Capacity Requirements for Frequency Regulation by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	5	5	5	5	5	10	10	10	10
Average Storage Duration (hr)	3	3	3	3	3	3	3	3	3

6.1.1.6 Demand Response (Grid)

The demand response service allows the customer battery energy storage systems to store the clean energy generated by a home solar system and provide backup energy when it is needed. The demand response service of such devices requires a communication system with the utility grid operator so that the charging or discharging actions can also be taken by the central dispatcher. Such service can be used to lower or increase the demand when needed.

Methodology for Sizing: To get the best result from the demand response service, 7.5% of the peak demand by year is selected as the storage power capacity requirement. The duration of the storage systems should be similar to the peak duration, which is around 3 hours in Barbados. Storage capacity requirement for demand response by year is given in Table 14.

Table 14: Storage Capacity Requirements for Demand Response by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	13	13	14	15	15	16	18	19	20
Average Storage Duration (hr)	3	3	3	3	3	3	3	3	3

6.1.1.7 Solar Firming & Ramping

Due to the technical requirements, thermal generators have a ramping restriction. Although one of the highest ramping capabilities is observed in the oil-based thermal generators, due to the increased share of renewables in the Barbados generation fleet in the upcoming years, the ramping is not only related to the demand variance but also the renewable energy intermittency should be carefully studied. The energy storage systems are known for their high ramping capability much faster than any other generation unit. Therefore, storage systems can be also used to provide ramping support at the grid level and also work with the renewable generator in a hybrid structure.

Methodology for Sizing: To evaluate the storage power capacity requirement for ramping service, the hourly dispatch of storage units is categorized into two: ramping due to renewable intermittency only and hybrid ramping due to demand and renewable generation variance. The difference of two consecutive hours in the net demand is defined as the ramping requirement that should be satisfied by the storage systems and the non-renewable generation sources. The discussion on the impact of ramping allowance for renewable firming on the storage sizing is given in Chapter 5. While the 20% and lower ramping allowances can decrease the risk of unpredictability by having firm renewable, they would cause unnecessary limitations on the solar generator that can be accommodated by the grid. 40% or higher ramping allowance; on the other hand, lowers the size of the storage required while increasing the risk of intermittency. Therefore, the ramping allowance for establishing the expected size of storage systems in Barbados per year is selected to be 30%. Therefore, 30% of the maximum hourly ramping requirement in a year is reported in Table 15.

The ratio between the daily energy stored for ramping and the maximum daily storage power capacity is the required duration of the storage systems. Storage power capacity requirements for ramping (utility-scale solar) by year are also given in Table 15.

Table 15: Storage Capacity Requirements for Ramping by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	17	29	41	64	88	99	110	122	145
Average Storage Duration (hr)	2	2	2	2	2	2	2	2	2

To illustrate the ramping requirement after a significant increase in the renewable share, a typical week of 2030 is selected and visualized in Figure 19. The highest upward ramping requirements are generally observed afternoon, where the solar generation starts to fade out from its daily max. In 2030, the ramp-up requirement may reach around 100MW per hour. However, the energy storage units ordered by a central dispatcher can reduce the ramp-up service provided by the non-renewable generator at those hours. Due to the increased installed capacity of solar and wind energy in Barbados, the simulation results show that there might be surplus renewable energy that would be curtailed unless stored during the day. Energy storage units can store the surplus renewable energy and that energy can be used to provide ramping up service after the renewable generation starts to decrease around noon time. Based on the calculations, the ramping requirement continues for around 4 hours daily. The storage units may reduce the previously required 100MW ramp-up service from the non-renewable generators to around 60-80MW per hour range.

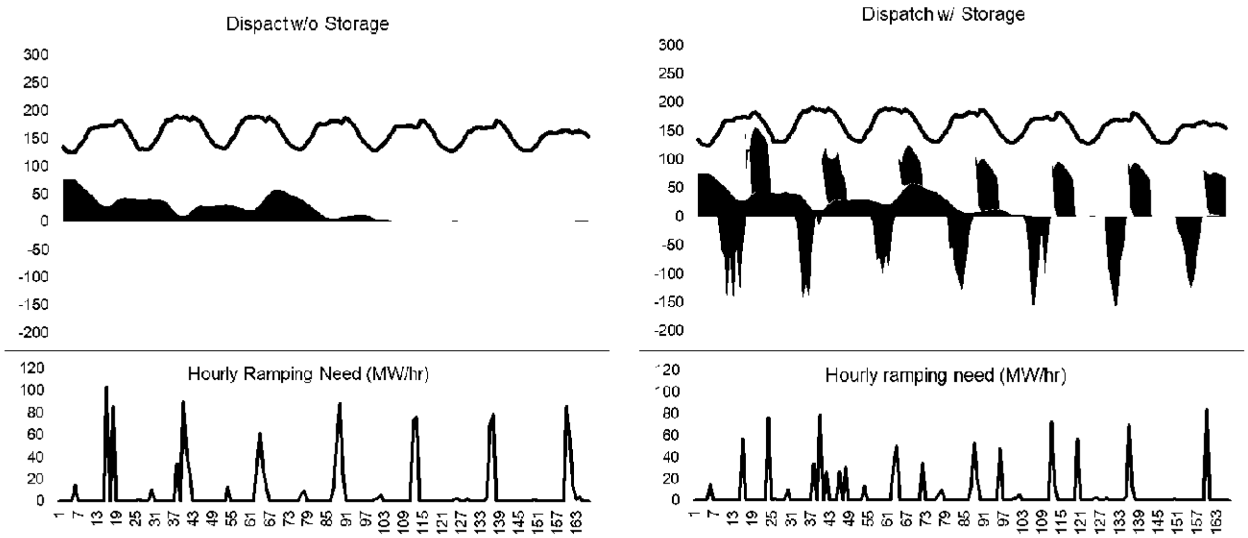

Figure 19: Typical Week of Dispatch in 2030 with and without storage units

Chart: Acelerex

The ramping in the traditional sense of power system operations are generally referred to as thermal generators to catch up with the varying demand to keep the frequency constant at around 50Hz. In a system with a high renewable share; however, the thermal capacity is expected to be less to provide such ramping service. Therefore, the energy storage units should be considered to take a portion of this service requirement. The size of the energy storage is getting larger if more ramping service is expected from those units; therefore, the solar firming approach would also help to reduce the intermittency of renewables to lower the ramping requirement. Based on the ramping allowance discussion above and in Chapter 5, renewable+storage hybrid systems can lower the ramping requirements that should be satisfied by the grid. The negative consequences of the renewables exceeding the given ramping allowance limit would be creating more pressure on the other thermal generators to ramp up and down. However, the pressure is not on their ability to do ramping but the amount of ramping service they can provide with less and less installed capacity in Barbados over the years.

6.1.1.8 Black Start

Based on US National Renewable Energy Laboratory (NREL), the black start is the ability of generation to restart parts of the power system to recover from a blackout. This entails isolated power stations being started individually and gradually reconnected to one another to form an interconnected system again. Black start is central to system restoration and recovery plans for system operators. In large power grids, black-start service comes from generators that can be started from an on-site auxiliary generator—without help from external power supplies. This is used to create an AC voltage waveform that other generations can synchronize to and start to generate additional power. For example, a diesel generator may be started with a local battery. This service might be critical for Barbados during the transition to a 100% renewable energy portfolio.

Methodology for Sizing: The storage power capacity required to provide black start service individually is traditionally done by the backup generators. The replacement of backup generators with storage systems may begin after 2025 and gradually increase to 20MW at the end of 2030. The storage power capacity requirements and their average storage duration for the black start are given in Table 16.

Table 16: Storage Capacity Requirements for Black Start by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	0	0	0	0	10	10	15	15	20
Average Storage Duration (hr)	1	1	1	1	1	1	1	1	1

6.1.1.9 Renewable Curtailment Reduction

Based on the hourly production cost simulations completed for the years between 2022 and 2030, 100% renewable generation is observed for a few hours per day in and after 2026. The renewable generation exceeds the demand, generally at noon. The dispatch of generators for a typical week selected from the year 2028 is shown in Figure 20. Several hours in the first day achieve 100% renewable energy and there would even be surplus renewable energy that is stored by the energy storage systems. However, the simulation results also show that even with storage systems proposed in the IRRP, there might be some hours that the surplus renewable energy is greater than the proposed storage capacity. This case is illustrated in the first, second, and the last day of the figure below.

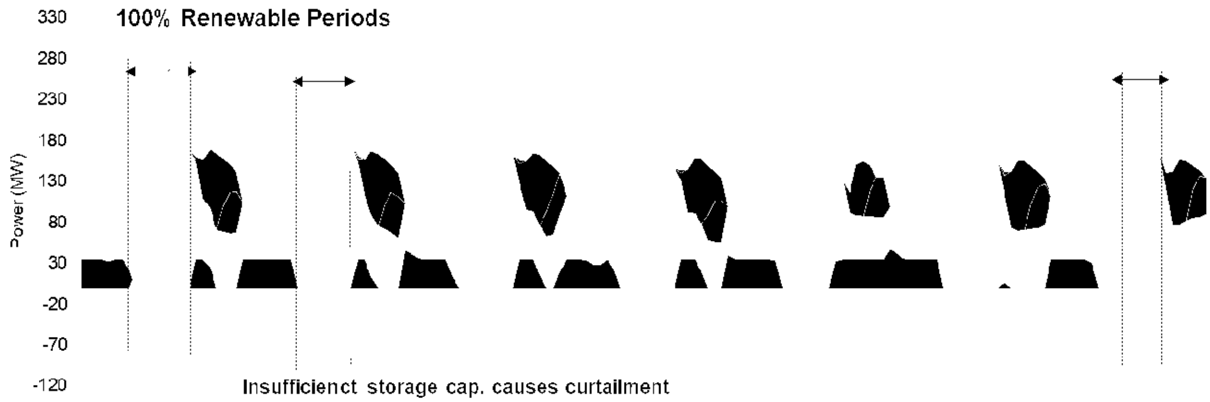

Figure 20: Typical Week Dispatch in 2028

The hourly dispatch simulations show that the total renewable curtailment begins in 2026 with a very limited hour; however, the estimated annual curtailment increases significantly after 2027 as shown in Figure 21. The IRRP storage capacity may not be sufficient to cover all renewable surplus after 2026. Therefore, additional storage capacity on top of the ones planned in the IRRP may be considered to reduce the curtailment and increase the overall renewable share of the fuel mix. Electric vehicle adaptation may also help reduce the insufficient storage capacity. The vehicle to grid (V2G) capability of future vehicles and grid infrastructure can open up opportunities for EV batteries to be used in helping grid operations. V2G technologies allow EV batteries to be charged or discharged when needed by the utility to support various services such as frequency regulation, peak shaving, and renewable curtailment.

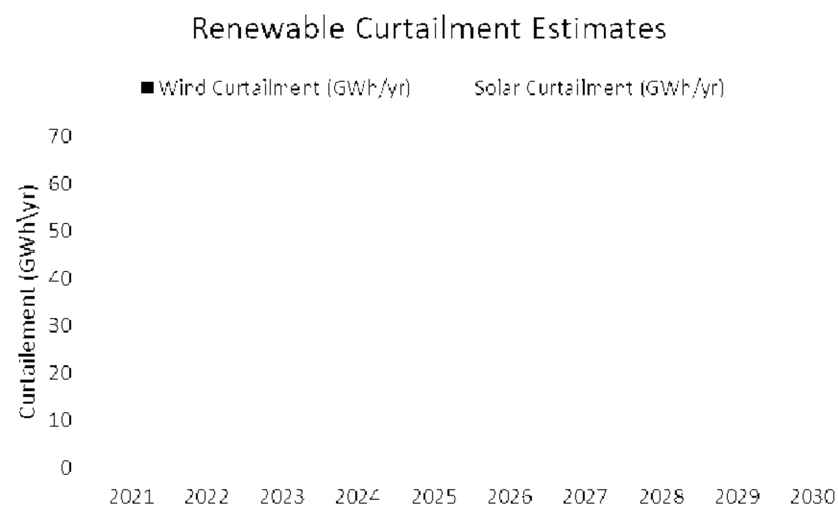

Figure 21: Renewable Curtailment Estimates

In order to utilize all renewable energy generation with no curtailment due to low demand than the supply, the storage power capacity requirement reaches 256MW in 2030 as shown in Figure 22.

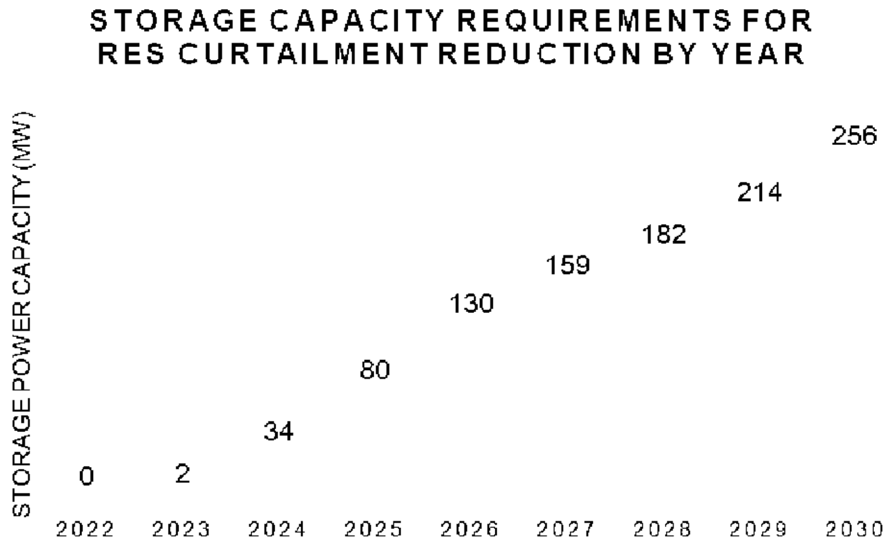

Figure 22: Power Capacity Requirements for Renewable Curtailment Reduction by year

Chart: Acelerex

This capacity requirement might rarely or usually occur based on the solar irradiation at that year. The maximum capacity requirements for individual renewable curtailment reduction services are given in Table 17.

Table 17: Storage Capacity Requirements for Renewable Curtailment Reduction by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	0	2	34	80	130	159	182	214	256
Average Storage Duration (hr)	0	1	4	5	6	6	6	7	7

6.1.1.10 Energy Service with Long Duration Storage (Grid)

Long-duration storage is an essential technology to bring reliability and supply security to the grid when the generation mix is mostly dominated by intermittent renewable resources. Once the share of solar and wind capacity increase in Barbados, there is the inevitable possibility of having not enough sunshine and wind throughout the day which results in insufficient generation capacity to satisfy the electricity demand. The lack of solar and wind generation can be tolerated either from non-renewable resources or preferably long-duration storage systems.

To understand the likelihood of having no solar for a day, the Trent solar plant daily capacity factor duration curve is illustrated in the figure below. The hourly real generation data of the existing solar plant is received from MESBE.

A method was developed for determining the cycling of long-duration storage for solar integration as the number of days solar capacity factor precipitously drops and that equals days of praying for the return of the stronger sun to power the grid. This method optically displays the days of years from the day of the best capacity factor to the days of the worst capacity factor and finds the crossing where storage will need to cover the risk of days of low solar capacity factor.

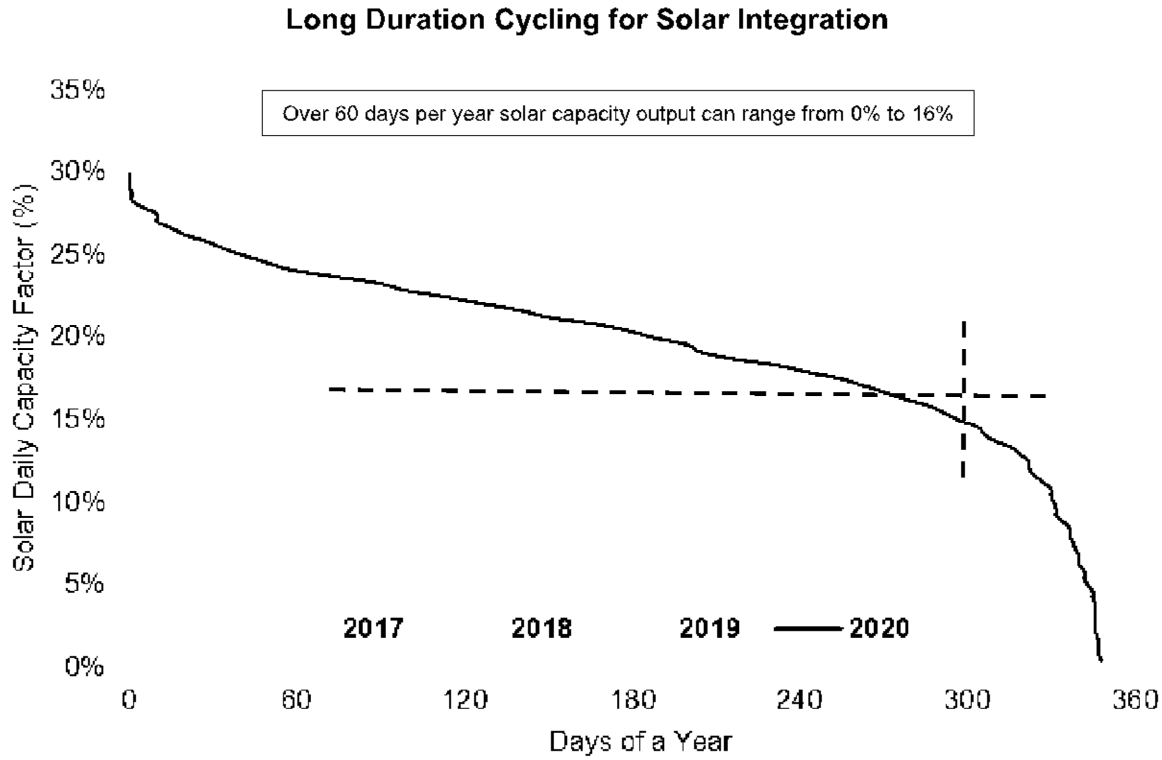

Figure 23: Trent solar plant capacity factor duration curve (2017-2020)
Data: MESBE, Chart: Acelerex

The duration curve shows that more than 300 days in the year 2020, the daily capacity factor was higher than 15%; however, 65 days in 2020 the daily capacity factor was below 15%; moreover, more than 15 days the daily generation was zero, meaning there was no sufficient solar radiation to generate electricity. The analysis of the previous years also shows that Barbados can have no solar generation during a day even if there are lots of solar installed capacity. A similar situation may also happen for wind generation as well.

To create a secure operation with high renewable integration, the long duration storage should be carefully considered to provide the necessary supply of energy when the solar and wind generation is not enough for Barbados.

6.1.1.1 Solar Capacity Factor Risk

The PV capacity factor duration curve in Figure 23 indicates that there is a 20% chance to have a low solar day in Barbados. Although it is high enough to think about how to manage the grid these days, another issue to consider is to have two or more consecutive days with low solar generation. To understand the solar capacity factor risk in Barbados, Acelerex analyzed the historical hourly generation data provided from the Trents solar generation plant to quantify the probability of several low solar days. The analysis, as illustrated in Figure 24, shows that the probability of having less than 15% capacity factor in Barbados was high as 22% in 2020 but the probability of having two consecutive days with low solar reduces to 7.14%. Barbados also had three and four days of low solar with 2.48% and 1.10% in 2020. These probabilities of course can change each year, so as seen in Figure 24, 2019 was a sunny year in Barbados so the probability of having a low solar day was 11% and the probability reduces to 2.2% for two consecutive low solar days and almost zero for three and more consecutive low solar days.

The long duration storage with 12 or more-hour duration can help with the daily risk of low renewable generation as well as reduce the solar capacity factor risk for consecutive low solar days. Moreover, another solution to mitigate and manage the risk is to have V2G technology implementations to satisfy distributed demand in emergency conditions of low solar output for consecutive days.

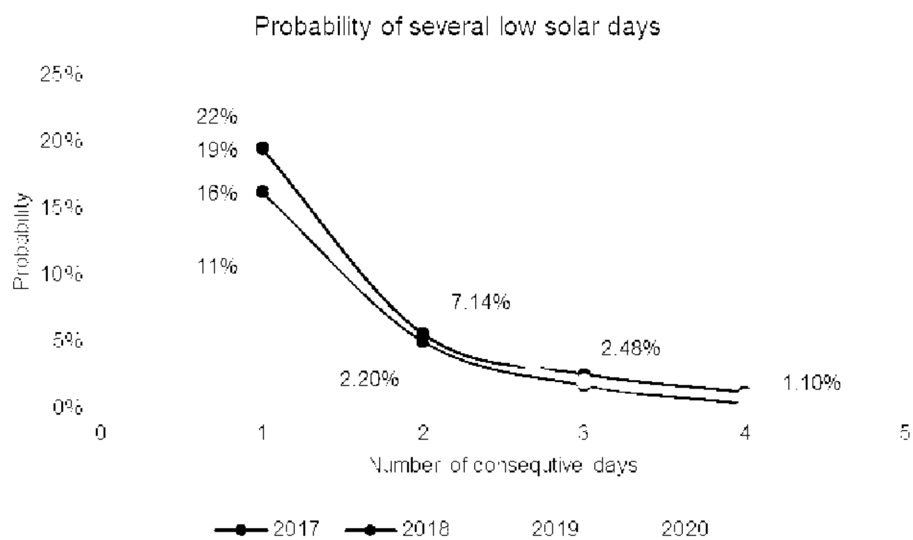

Figure 24: Probability of several low solar days (2017-2020)

Data: MESBE, Chart: Acelerex

6.1.1.2 Vehicle-to-Grid Technologies

The basic concept of the Vehicle-to-Grid (V2G) is based on delivering power from the battery of an electric vehicle to the grid when needed for enhancing the reliability of the system. Electric vehicles can also be used as storage devices. V2G technologies can increase the flexibility of the grid operations when the vehicle fleet is mostly dominated by electric vehicles. Barbados system is likely to have more renewable energy in the system than the demand in and after 2026. The V2G technologies can help reduce the renewable curtailment by storing the surplus energy to the vehicles and delivering the stored energy back to the grid when needed by the utility. Moreover, V2G technologies can help reduce the intermittency of renewables by delivering the stored energy in the vehicle's battery. This increased flexibility eases the operational difficulties of the renewable energy-dominated grid.

EV Charging (V1G): EVs and the charging stations that have the capability of only charging

- Consumers can manage their charging hours based on the TOU rates.
- Smart charging to counterbalance solar intermittency

EV-to-Grid (V2G): EVs and the charging stations that have bi-directional capabilities

- Consumers can manage locally the charge and also discharge providing BTM services such as TOU rate optimization, renewable shifting, and distribution capacity hosting.
- Consumers can get paid if they participate in to support grid and let the central control system regulate the charge and discharge.
- Consumers can get paid when connected to the VPP and contribute to all services it is providing to the grid.

Methodology for Sizing: Based on the estimates of EV growth (base case) provided in the Barbados 2021 IRRP for LDV, MDV and HDV an estimated peak load difference is determined which is contributed through EVs. Considering the adoption of V2G would be less compared to V1G as V2G requires bidirectional capabilities which add to the cost of development, 25% of EVs are expected to participate in the energy market with V2G capabilities and remaining with V1G. The storage power capacity estimates for V1G and V2G are given in Table 18. The duration of both the services would range from 2-4hrs depending on the type of chargers.

Table 18: Storage Capacity with Projected EV Growth by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
EV Charging V1G (MW)	3	8	9	13	16	21	34	39	47
EV-to-Grid V2G (MW)	1	3	3	4	5	7	11	13	16

To increase the participation of EV owners in V2G technology options in Barbados, various TOU tariffs can be developed to create the financial background of the program. With the increased share of renewables in the generation fleet, the net demand begins to take the shape of a duck curve in which the time of peak demand may change in the future. Therefore, V2G integrated vehicles and utility infrastructure can help reduce the impact of the duck curve and increase the reliability of the system.

6.2 Services Controlled by Local Dispatcher

The following sections describe each energy storage service that can be operated by a local controller. The controller devices might be in the range of very simple to very complex; however, their operational principle is the requirement of local information only such as local voltage, frequency, and power consumption. The operational decisions of the energy storage system can be made based on the current status of the local grid.

6.2.1.1 Renewable Firming (Local)

Increasing renewable share in the generation fleet has challenges. It is harder for the system to absorb more renewables without a proper storage allocation. Moreover, possible wind and solar curtailments may hurt owners as well. Renewable firming can create new opportunities. It can help increase revenue sources. It is relevant for new customer channels such as corporate PPAs. Renewable firming by definition is maintaining the output from a variable, intermittent power source, such as wind or solar, for a committed period of time. Possible firming options are firming over seconds to minimize costs, firming over a day to better match a corporate PPA, or firm over the year to better match portfolio requirements.

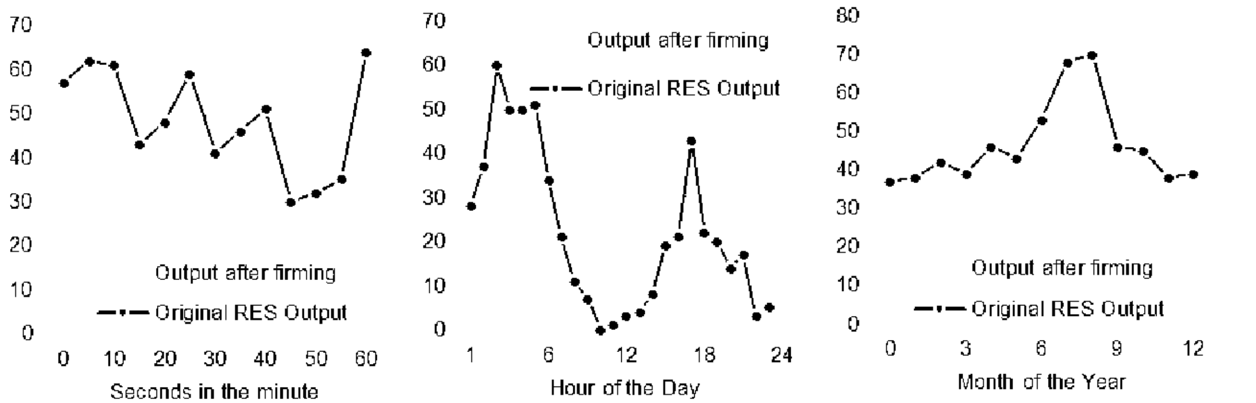

Figure 25: Renewable Firming Options

Chart: Acelerex

Energy storage systems, especially chemical storage options like lithium batteries provide fast firming for short durations and are quick to build. They can be co-located with renewable assets. They are modular with a small footprint and have a very fast response for short-term firming. The service generally requires medium duration storage at most 4 hours.

Methodology for Sizing: 5% of the total installed capacity of wind and solar is allocated to provide local renewable firming service. These physical units can be operated by the plant owner and operator rather than a central dispatcher. The average storage duration is 4 hours for storage systems to provide local renewable firming.

Table 19: Storage Capacity Requirements for Renewable Firming by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	4	6	8	11	13	15	16	17	19
Average Storage Duration (hr)	4	4	4	4	4	4	4	4	4

6.2.1.2 Frequency Response (Local)

The energy storage solution is a modular, fast-responding solution to frequency response service which is typical cannot be provided by behind-the-meter or distribution system connected devices. However, energy storage can be deployed behind the meter or at the local transformer level and provide a frequency response service for the local customers. This service is not tracking the grid frequency but the local frequency to regulate the frequency. The service can increase the local resiliency measures, the local power quality, and it is considered as insurance for an emergency, which may normally cause a local brownout.

Methodology for Sizing: 30% of the total storage capacity allocated for grid-scale frequency regulation is assumed to be distributed around Barbados and operated individually by local frequency measurement devices. Due to the adaptation period of such service, the requirements are started after 2025. The storage power capacity requirements for local frequency response by year and their respective durations are given in Table 20.

Table 20: Storage Capacity Requirements for Local Frequency Response by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	0	0	0	1.5	1.5	3	3	3	3
Average Storage Duration (hr)	-	-	-	3	3	3	3	3	3

6.2.1.3 Virtual Inertia

The virtual inertia service provides a voltage source and injects or receives power automatically when the grid voltage moves away from the battery voltage. It depends on how much trouble the grid can get into in 10 to 100-millisecond delays of Fast Frequency Response (FFR). The Barbados power systems won't be faced with such a problem for a couple of more years, but as more synchronous generators retire this won't be the case. The frequency will fall or rise much quicker if there is less inertia in the system, making this technology and virtual inertia as a service more and more critical moving forward for Barbados.

To maintain frequency in its nominal value, power systems rely on synchronous machines connected to the grid, which store kinetic energy automatically extracted in response to a sudden power imbalance. However, conventional generators are being replaced by renewable energy generators. The massive penetration of especially solar photovoltaic into the grid can reduce the effective inertia of the power system due to their connection to the grid through inverters which electrically decouple them from the grid. This inertia reduction affects the system's reliability, compromising the frequency stability [5]. A power system with synchronous and virtual inertia is illustrated in Figure 26. Energy storage systems can also provide virtual inertia to the grid when they are coupled with solar PV or wind units.

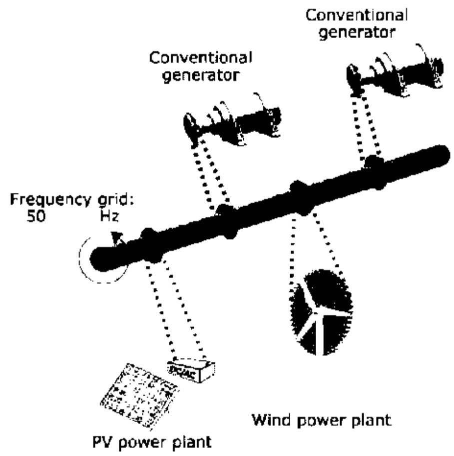

Figure 26: Power system with synchronous and virtual inertia

Image: A Review of Virtual Inertia Techniques for Renewable Energy-Based Generators

BLPC has an under-frequency load shedding scheme which sheds about 1500 kW in 30mins as the first step when frequency goes down to 49.6 Hz. Subsequent load shedding is performed as shown in Figure 27 when frequency keeps decreasing. This load shedding scheme allows the system to remain stable and synchronized and avoid any black-out conditions.

[redacted]

Figure 27: BLPC Under Frequency Load Shedding

Such under-frequency conditions can happen more often when solar generation decreases unexpectedly. The power deficiency can be fulfilled by the long-duration energy storage sized to the current load shedding scheme. To counter the under-frequency up to the step of 48Hz in the current scheme, a supply of 23.5 MW is required until the load decreases or other resources come online. Long-duration energy storage planned for low solar generation days can be used here. The storage power capacity and its duration requirements for virtual inertia service by year are given in Table 21.

Table 21: Storage Capacity Requirements for Virtual Inertia by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
Average Storage Duration (hr)	1	1	1	1	1	1	1	1	1

6.2.1.4 Local Services

An energy storage system can be located next to a renewable energy source or even demand to provide local services such as demand charge management, voltage setpoint control, transient voltage response, flicker control, power factor control, and manual charge/discharge. The energy storage systems which provide local services do not require a communication channel with the utility operator and do not necessarily operate by a central dispatcher. The local measurements of voltage, frequency, and power generation/consumption are required to control these storage systems. The storage power capacity and its duration requirements for local services by year are given in Table 22.

Table 22: Storage Capacity Requirements for Local Services by Year

Service	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage Power Capacity (MW)	0	0	2	4	8	12	15	20	20
Average Storage Duration (hr)	-	-	3	3	3	3	3	3	3

The definitions of local services and the details from the technical aspect are given below. The services covered are voltage setpoint control, transient voltage response, flicker control, power factor control, and manual charge/discharge.

Voltage Setpoint Control: In order to operate the power grid in the allowable voltage limits, there are traditional engineering solutions to increase the voltage locally such as capacitors, static synchronous compensators, or flexible AC transmission/distribution system (FACTS) devices. Those devices are following the local measurement of the voltage at the nearest bus to keep the voltage in the allowed operational region by the grid code. Energy storage systems can also provide such services due to their integrated inverters. These inverters can be selected to provide four-quadrant operational flexibility to adjust the real and reactive output to create a setpoint control of voltage.

Flicker Control: For balancing energy generation, solar and wind generators are being integrated into the utility grid at the same location to form the hybrid power system. This has been achieved by the use of power electronic converters which are non-linear in nature. Further, the variability of solar and wind energy generation also deteriorates the quality of power in the hybrid grid. Any disturbance developed in the hybrid grid affects system parameters and power flow due to the non-linearity of the system and variability of renewable generation [6].

Power Factor Control: The power factor control service increases the grid efficiency by increasing the power factor by manipulating the reactive and active power with the energy storage system. The power factor control can also be used to locally manage reactive power consumption.

Manual Charge/Discharge: The manual charge and discharge service is an owner-oriented service generally for bill management or roof-top solar system support. The charge and discharge decisions are solely based on owner preference and it doesn't require any communication with the utility grid.

6.3 Stacked Services

The practice of 'stacking' grid services aims to maximize potential profits from energy storage services. Stacked services benefits may be broken down into capacity savings, fuel savings, Variable Operation and Maintenance (VO&M) cost savings, Fixed Operation and Maintenance (FO&M) cost savings, primary, secondary, and tertiary reserve savings, forecast error savings, black start savings, capacity deferral, T&D deferral, and cost to load savings. These services can be thought of as stacked in terms of capacity nominated for service as well as energy allocated. Figure 28 shows a visualization of the stacked services concept.

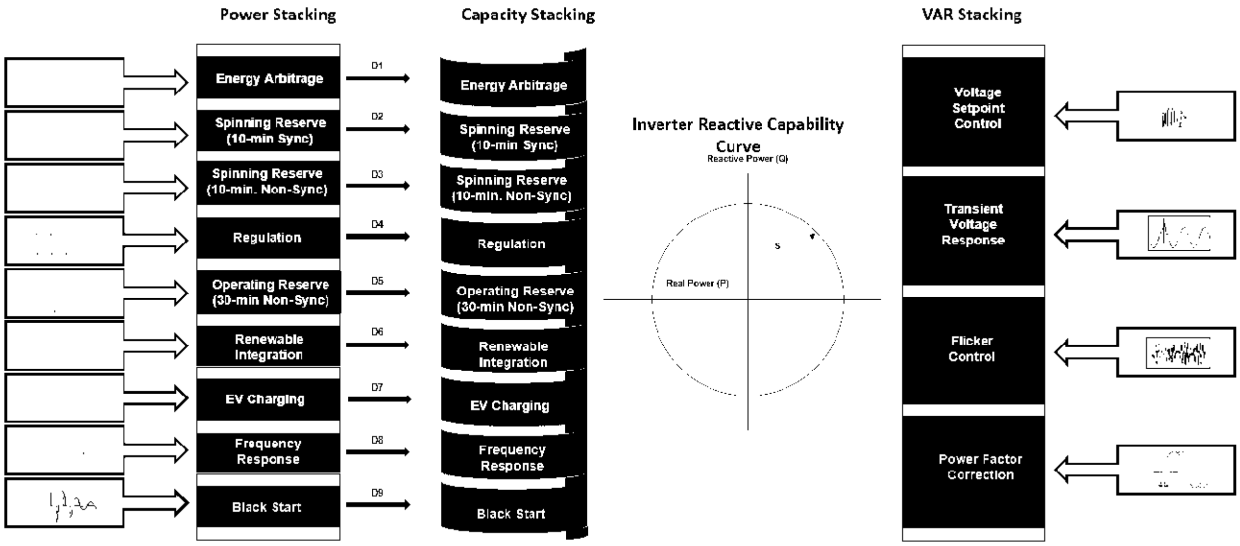

Figure 28: Stacked services in nominated capacity and allocated energy stacks

Source: Acelerex

Other benefits of stacked services include increased return on investment of energy storage due to optimized utilization, improvement of microgrid operation when deployed in conjunction, and stabilization of energy markets due to increased reliability.

The stacked services emulator (SSE) reveals the possibility of the stacked services approach in Barbados. A typical week in 2030 is illustrated in Figure 29. Due to the high installed capacity of wind and solar, there are hours during the day in which the renewable energy generation is higher than the demand, therefore, we observe a couple of energy storage services are activated around noon time. A portion of the charging of storage from surplus renewables is related either to energy arbitrage or renewable curtailment reduction. After the renewable energy generation is getting lower than the demand, those already charged storage systems now can provide energy to the grid by either lowering the production cost of electricity or shaving the peak. The demand response-related storage service can be activated based on a tariff or pre-determined schedule to lower the demand to keep the system working with 100% renewables.

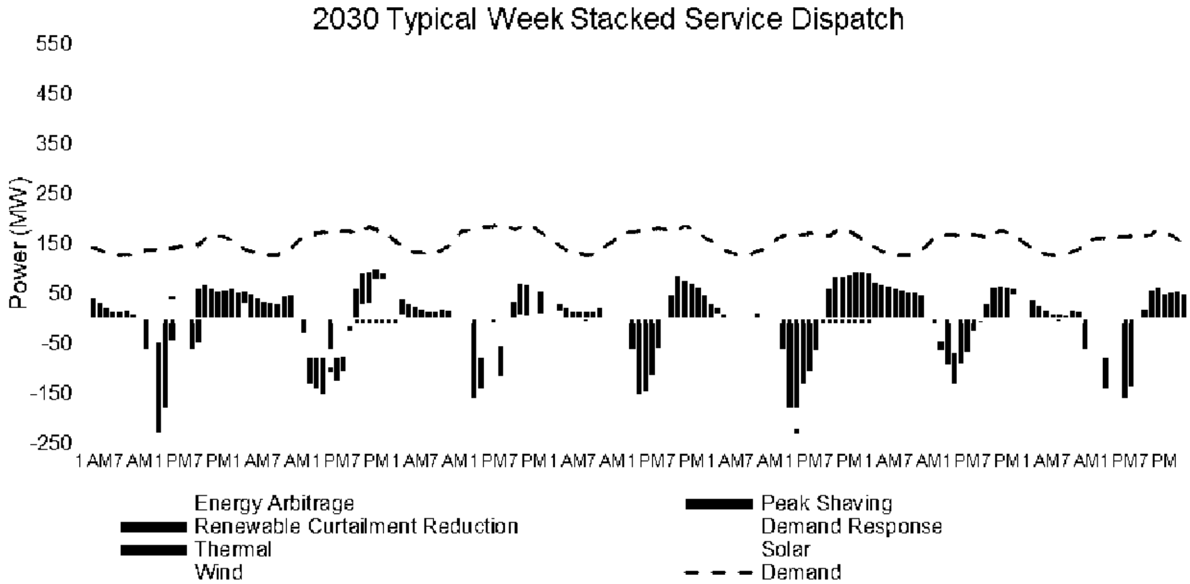

Figure 29: A Typical Week Stacked Service Dispatch of Storage

6.4 Virtual Power Plant

A virtual power plant (VPP) is a cloud-based distributed power plant that aggregates the capacities of heterogeneous distributed energy resources for the purposes of enhancing power generation, as well as trading or selling power on the electricity market. A VPP is a network of decentralized, medium-scale power generating units such as wind farms, solar parks, and Combined Heat and Power (CHP) units, as well as flexible power consumers and storage systems.

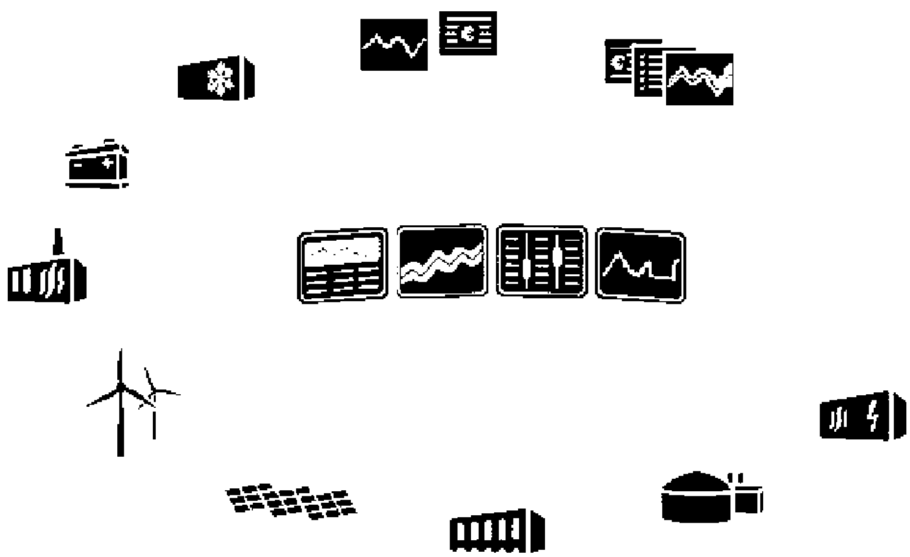

Figure 30: Virtual Power Plant Concept

The interconnected units are dispatched through the central control room of the VPP but remain independent in their operation and ownership. The objective of a VPP is to relieve the load on the grid by smartly distributing the power generated by the individual units during periods of peak load. Additionally, the combined power generation and power consumption of the networked units in the VPP are traded on the energy exchange.

The VPP solution, which is developed to prevent cables from reaching their maximum carrying capacity and therefore eliminating the need for renewal. The instant status and capabilities of these systems can be monitored by smart software, and a fast, clean, and environmentally friendly response can be provided to electrical needs. Therefore, the VPP provides reliability and resiliency so that local power outages can be prevented. Environmentally friendly solar energy production and the use of storage technologies that ensure that no energy is wasted distinguish the VPP solution from traditional solution methods in a positive way, due to its zero environmental impact.

A VPP resource can provide multiple BTM services such as Demand Charge Management, TOU Rate Optimization, Renewable Shifting, Peak Shifting, and others. In addition to that, aggregate VPP sources can provide wholesale market services such as Energy Arbitrage, Frequency Regulation, Spinning Reserves, and others.

For instance, in 2019, Tesla installed 5kW rooftop solar with 13.5kWh Tesla PowerWall batteries on over 1,000 low-income homes which are interlinked to make a VPP in Australia. The Australia Energy Market Operator (AEMO) released its first review of the VPP installation and showed excellent results. The VPP helped maintain grid stability when a coal-fired unit in Queensland tripped offline and reduced system supply by 748 MW in October.

7. 2030 and beyond with 100% Clean Energy

The previous chapters cover the storage system services and their capacity requirements between 2022 and 2030. This chapter covers the potential future of the Barbados system after 2030. The least-cost capacity expansion selects the generators from the list of possible investment options after 2030. After the retirement of several fossil fuel-based generators before 2030, the retired installed capacity is replaced by solar panels and wind turbines. A similar trend is also being followed after 2030. The online thermal units (GT units) which arrive at the age of 40 in the 2030s retire in 2035. The retired capacity is replaced by solar and wind expansions after 2030 as shown in Figure 31.

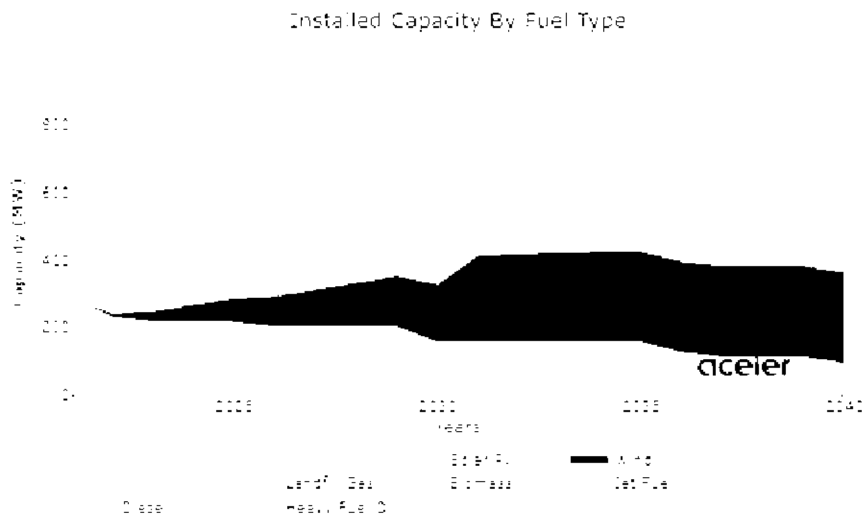

Figure 31: Installed Capacity by Fuel Type after 2030

Source: Acelerex

The economic expansion of solar and wind increases the renewable capacity by 42% in 2040 compared to the capacity in 2030. The renewable energy capacity increase after 2030 is less than before 2030, but the increasing trend continues as shown in Figure 32.

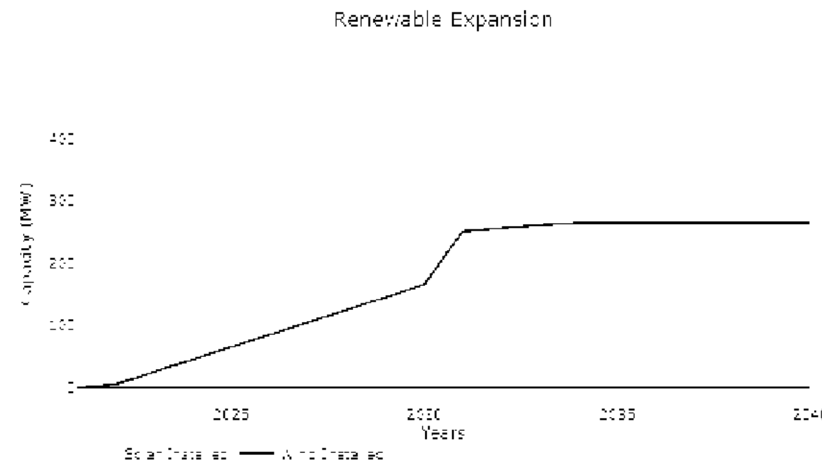

Figure 32: Renewable Capacity Expansion (2022-2040)

Source: Acelerex

A similar growth rate is observed before and after 2030 for solar technologies in the renewable capacity expansion plan. The installed capacity of solar reaches 431 MW in 2035 and 461 MW in 2040. The increased share of renewables in the generation fleet should be coupled with storage systems to operate the grid securely. The storage expansion plan after 2030 shows the high-capacity requirement for storage to provide the services required by the grid. One of the critical services is to reduce the renewable curtailment due to the increased solar capacity after 2030. The storage capacity expansion is shown in Figure 33.

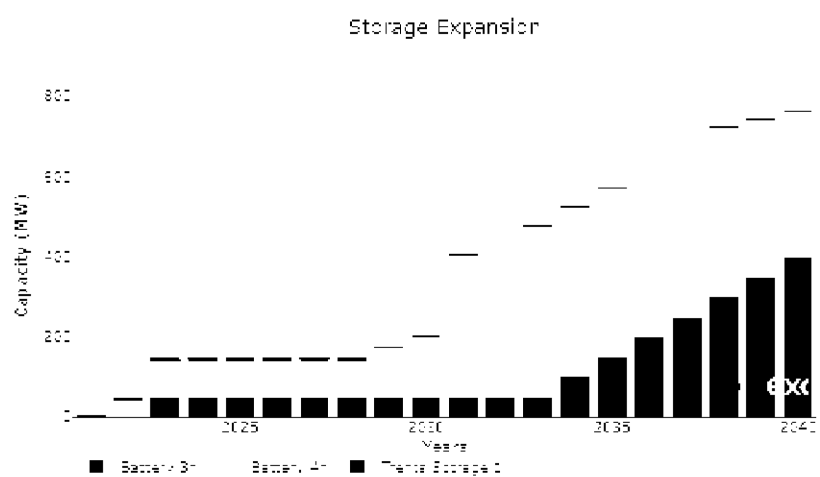

Figure 33: Storage Capacity Expansion (2022-2040)

Source: Acelerex

The storage systems with 3-hour energy capacity reach 400MW in 2040, while the systems with 4-hour energy capacity reach 390 MW. Although the renewable share increases in the fuel mix of Barbados over time, the need for non-renewable generation units is not disappeared. The annual generation mix study shows that non-renewable generators may be called upon a couple of hours during a day for power and demand balancing or ramping purposes. The annual generation mix of Barbados is illustrated in Figure 34.

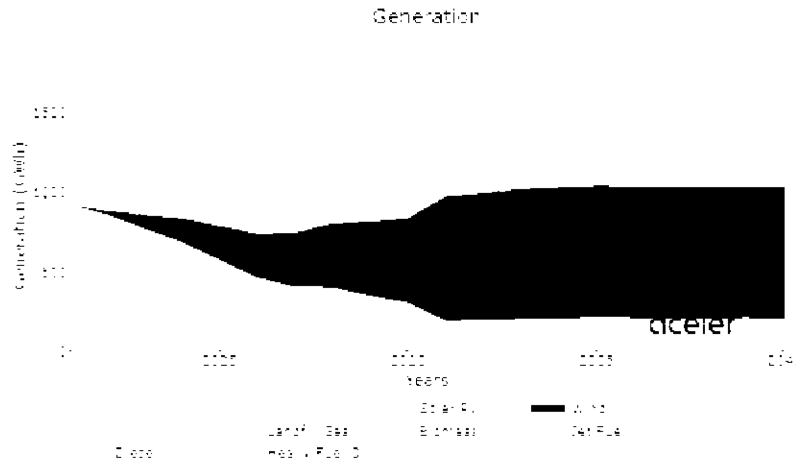

Figure 34: Generation mix (2022-2040)

Source: Acelerex

With the growth of commercial and industrial demand in Barbados, the annual energy demand increases from 1,368 GWh in 2030 to 1,607 GWh in 2040. The renewable share in the generation mix also increases as well with the renewable capacity expansion after 2030. The share of solar and wind reaches 36.2% and 51.3% in 2040 in Barbados as shown in Figure 35.

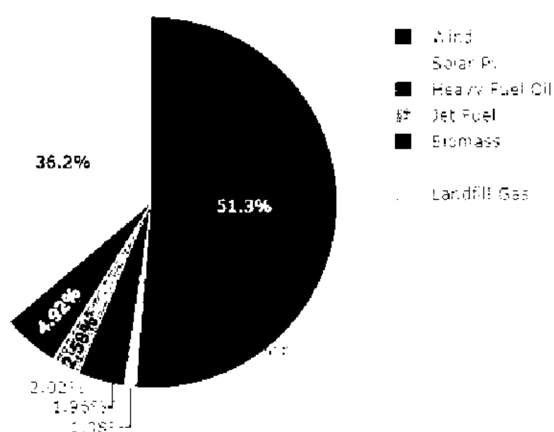

Figure 35: Fuel mix in 2040

Source: Acelerex

7.1 Recycling of Storage Systems

While clean energy technologies have many benefits compared to burning fossil fuels, they still have environmental considerations that need to be carefully and responsibly mitigated or managed. Like other equipment and machinery, they do eventually wear out and reach the end of their useful lives. A key aspect of responsible clean energy would be improving the reuse and recycling of clean energy components.

Although Lithium-ion batteries aren't the only kind of grid-scale batteries (others include redox flow and newer zinc-hybrid batteries), Li-ion batteries are now being used at a much larger scale to store energy for electric vehicles (EVs) and as storage for renewable energy systems like wind and especially solar. However, there is not a single type of Li-ion battery. They may be comprised of a variety of chemistries, which is one of the challenges that come with recycling them through varying stages.

The challenge in recycling or disposing of Li-ion batteries is that they are classified as hazardous waste, due to their chemistries and combustibility. Having different chemistries, including lithium manganese oxide and lithium nickel cobalt aluminum oxide, complicates the logistics of recycling due to the possibility of mixing different chemicals in unfortunate ways.

As the market for EVs increases, manufacturers aim to match the recycling success by collecting the EV batteries back in mass for secondary markets (such as used in energy storage systems) or recycling. For that to happen, new recycling infrastructure and policy incentives are needed to move the market in a self-sustaining direction.

8. Economics

8.1 Installed Capacity Addition Forecast

To achieve 100% decarbonization, the new installed capacity is projected using the expansion analysis. Figure 36 shows the annual new resources required for Barbados which adds up to 294MW of solar resources, 166MW of wind resources, and 280MW of storage by 2030. The size requirements in MW represent the output power capability. The amount of storage required year-by-year as indicated in the figure and the table below is technology independent. Due to the fact that the round-trip efficiency of different storage technologies varies, if a specific storage technology is selected then the losses will have to be factored into the energy amount required. The losses associated with specific technologies have an impact on the energy component of the storage, not the power component.

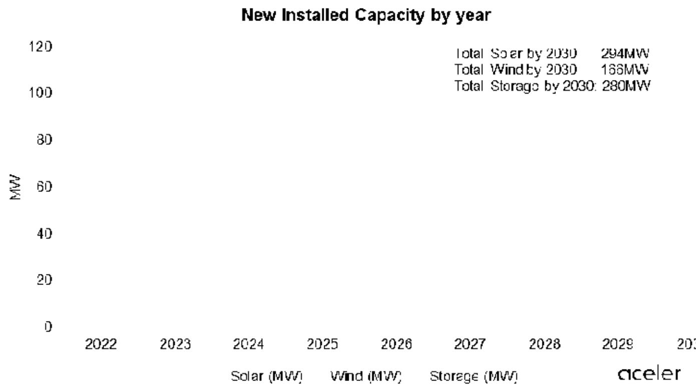

Figure 36: Annual New Installed Renewables & Storage Capacity

The annual additions of new renewable and storage resources as given in Table 23 will start replacing the existing fossil fuel generators and eventually generate electricity without carbon emissions.

Table 23: Annual New Installed Renewables & Storage Capacity by Year

Expansion (MW)	2022	2023	2024	2025	2026	2027	2028	2029	2030	TOTAL
Solar	34	32	29	46	45	24	22	22	40	294
Wind	6	20	20	20	20	20	20	20	20	166
Storage	40	30	30	30	30	30	30	30	30	280
Storage	160	120	120	120	120	120	120	120	120	1120

8.2 Overnight Costs

For the new installed capacity requirement projection to achieve 100% decarbonization, total overnight cost investments of $786 million would be required by 2030. Annual overnight cost investments in renewables and storage resources are shown in Figure 37.

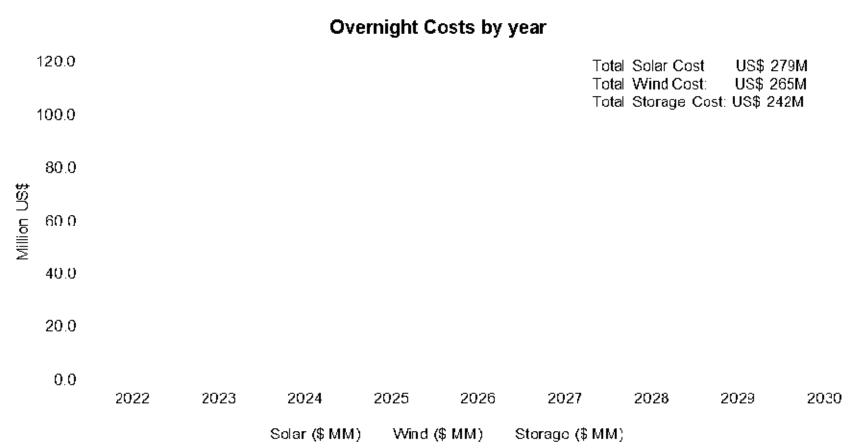

Figure 37: Annual Overnight Cost for New Installed Renewables & Storage Capacity

The overnight cost analysis suggests a total of $279 million for Solar resources, $265 million for Wind resources, and $242 million for Storage resources as shown in Table 24. Annual average investments of $87 million would be required until 2030 to achieve the set targets.

Table 24: Annual Overnight Cost for New Installed Renewables & Storage by Year

Overnight Costs ($ Million)	2022	2023	2024	2025	2026	2027	2028	2029	2030	TOTAL
Solar	44.1	38.0	31.6	45.8	41.1	20.1	16.9	15.4	25.7	278.6
Wind	11.5	36.6	35.1	33.6	32.2	30.9	29.6	28.3	27.1	264.9
Storage	45.1	31.4	29.3	27.2	25.3	23.5	21.9	20.3	18.9	242.9

8.3 Fixed O&M Costs for Renewables & Storage

Over the period of 2022 to 2030, the annual Fixed Operation and Maintenance (FOM) costs of renewables and storage are estimated with the expansion analysis. Annual FOM costs for running the renewables and storage resources are shown in Figure 38.

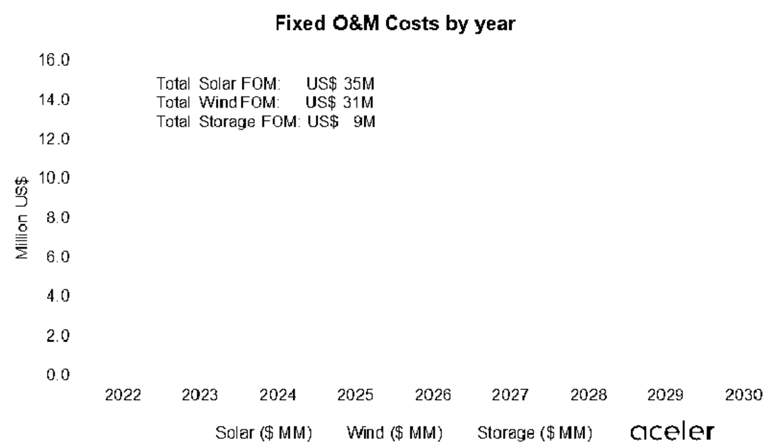

Figure 38: Annual Fixed O&M for Renewables & Storage

The FOM analysis suggests a total of $35 million for Solar resources, $31 million for Wind resources, and $9 million for Storage resources as shown in Table 25. An annual average FOM of $8.4 million would be required to operate these resources.

Table 25: Annual Fixed O&M for Renewables & Storage by Year

Fixed O&M ($ Million)	2022	2023	2024	2025	2026	2027	2028	2029	2030	TOTAL
Solar	1.5	2.1	2.6	3.5	4.3	4.7	5.1	5.5	6.2	35.6
Wind	0.2	1.0	1.8	2.6	3.4	4.2	5.0	5.8	6.6	31.0
Storage	0.2	0.4	0.6	0.8	1.0	1.1	1.3	1.5	1.7	8.6

8.4 Fixed O&M Costs for Thermal Plants

Over the period of 2022 to 2030, the annual Fixed Operation and Maintenance (FOM) costs for thermal plants are estimated with the retirement analysis. Annual FOM costs for running the existing thermal resources are shown in Figure 39.

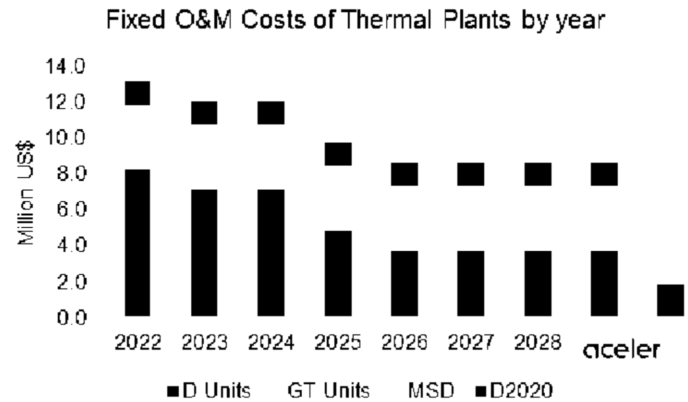

Figure 39: Annual Fixed O&M for Thermal Plants

The FOM analysis suggests a total of $44.3 million for Diesel units, $15.7 million for GT units, and $16.8 million for Resiliency Bridge, and 10.5 million for D2020 as shown in Table 26.

Table 26: Annual Fixed O&M for Thermal Plants by Year

Fixed O&M ($ Million)	2022	2023	2024	2025	2026	2027	2028	2029	2030
D Units	8.3	7.1	7.1	4.9	3.8	3.8	3.8	3.8	1.9
GT Units	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
MSD	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
D2020	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	0.0

8.5 LCOE of Resources and System

A simplified Levelized cost of energy (LCOE) for the planned resources and system with project capacity mix is evaluated over the economic life of the planned resources using the overnight capital costs, O&M costs, and energy produced. For analysis, individual resources, and combined resources LCOE is evaluated over the planning horizon.

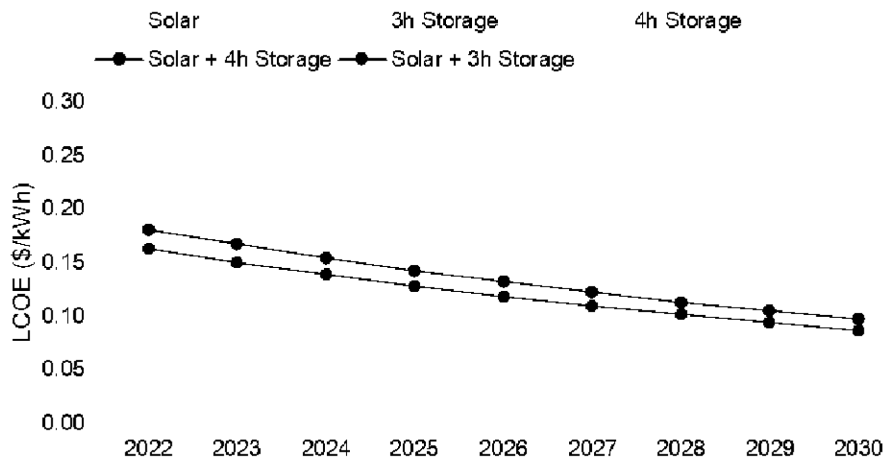

Figure 40: Solar and Storage LCOE between 2022 and 2030

Source: Acelerex

There are 5 different technologies as shown in the legend of Figure 40. Solar technology contains only Solar PV Panels investments evaluated over 10 years of the planning horizon. The applications in Barbados for energy storage require a wide range of duration. For LCOE calculations, 2 types of storage systems with the duration of 3 hours and 4 hours are evaluated.

The system LCOE is calculated by considering total supply in the Barbados generation fleet over the planning horizon. The LCOE is calculated using the solar capital and fixed costs; wind capital and fixed costs; storage capital, fixed, and variable costs; generation capital, fixed costs, and variable costs, fuel costs.

The system LCOE goes down as fossil fuel purchases are reduced and renewable technology is adopted.

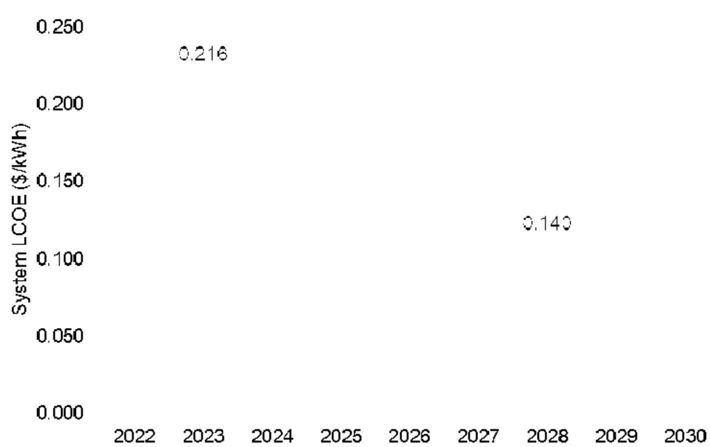

Figure 41: System LCOE between 2022 and 2030

Source: Acelerex

9. References

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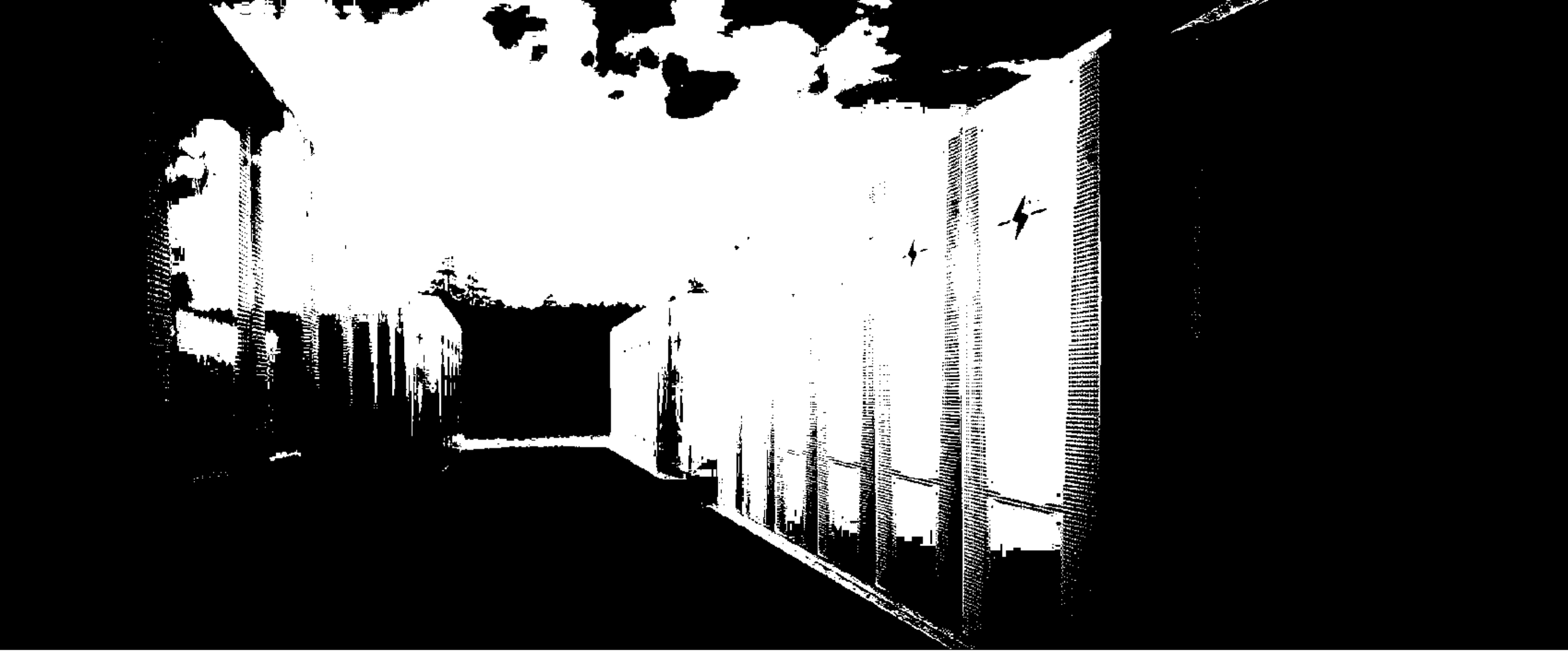


10. Appendix-A: Barbados Energy Review

This section covers the review of the Barbados Energy sector. The policies subsection explains the possible future scenarios that are considered in the government reports. The generation subsection provides an insight into the supply side of the system with respect to fossil fuels-based and renewable energy bases generation capacity. The energy utilities and market subsection discuss how the market structure works in Barbados. And lastly, a review of the 2021 Barbados Integrated Resources and Resiliency Report is given in this chapter.

10.1 Current Policies

Barbados has planned for shifting the country away from oil consumption to generate electricity [7]. The plan is driven by:

- The significant potential of renewables available across the island
- Capital costs decline of renewable resources and energy storage systems
- Developing of new emerging technologies with growing confidence in their performance such as electric vehicles EV and different storage technologies.
- Climate change risks (Paris agreement commitment)

The renewable portfolio standard is to achieve a decarbonized power grid in Barbados by 2030. This shift is set out in the Barbados National Energy Policy 2019-2030 (BNEP 2019-2030) document. The policy aims to transform into an efficient, diversified, and environmentally sustainable energy system for the country and includes six main goals to reach the required transformation.

1. Provision of reliable, safe, affordable, sustainable, modern, and climate-friendly energy service to residents and visitors
2. Zero domestic fossil fuel consumption
3. Export hydrocarbons released by land and offshore
4. Maximize the participation of renewable energy resources and storage systems in the distributed level
5. Minimize the outflow of foreign exchange

10.2 Generation Capacity

The generation capacity in 2021 consists mostly of fossil fuel plants (92%), which are HFO (41%), Jet A1(25%), and Diesel (26%) see Figure 42. It should be noted that the main fuel type of overall generation units is HFO in 2021. Moreover, Diesel and Jet A1 fuels penetrate almost the same percentage. Lastly, the solar capacity forms only eight percent of the total installed capacity.

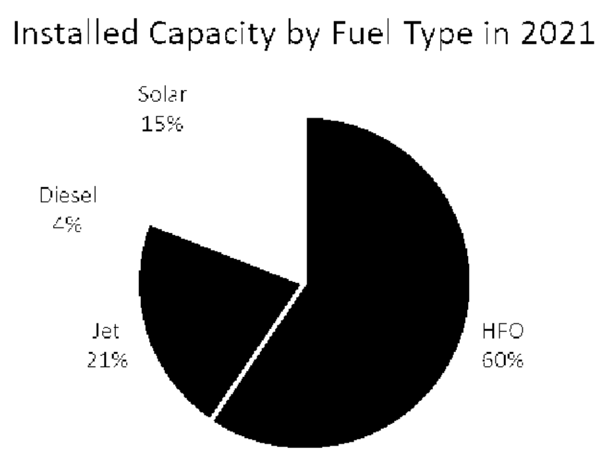


Figure 42: Barbados Installed Capacity by Fuel in 2021

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

10.3 Energy Utilities and Market

Barbados is an island with limited amounts of energy resources, covering its energy demands by oil products mainly imported from outside the country, although it produces natural gas, biomass, and cruel oil. The total energy consumption in Barbados reaches around 4,200 GWh. The transportation sector occupies the largest energy end-user while industrial and residential sectors have witnessed a decline in energy consumption over the last two decades. [7]

The government of Barbados (GoB) holds the authority of oil and gas production as well as imports owning the Oil Company Limited (BNOCL) and the National Petroleum Corporation (NPC). GoB key interest in the oil production sector limits the possibility of private oil companies participating in the production or imports. They mainly participate as distributors and retailers. The oil market in Barbados is operated as a private company and adopts market prices. this doesn't work for natural gas that has been sold at submarket prices for a long time.

Regarding the electric power sector, it is dominated by a private utility named Barbados Light and Power Company (BLPC) and owned by an energy holding company located in Canada. The electricity market is operated by the company through a long-term license agreement. BLPC plays several roles such as; transmission system operator (TSO), distribution system operator (DSO) as well as the responsibility to generate electricity to cover the island's demand. Fair Trading Commission (FTC) regulates the capital expenditure recovered by BLPC from customers as well as the tariff level.

Like many countries, an increasing interest has been shown in Barbados to decentralize the electricity generation and power market towards a more clean, reliable resilient, and sustainable power grid. This interest targets the residential level by rooftop PV systems as well as larger-scale energy resources mainly solar systems to be integrated at transmission and distribution levels. A Feed-in Tariff (FiT) is created by the Energy Rider scheme to encourage decentralized generation. GoB is currently developing new market models and regulatory to manage the energy businesses of independent resources such as renewable systems and storage

10.4 Electrical Vehicles

Barbados is a very suitable island for electrical vehicles due to its small size. Moreover, the GoB has approved the deployment of 43 charging stations as seen in Figure 43. However, they are not available to the public yet. The public chargers on the island are installed by MegaPower. Details of the charging stations can be found on the plug share website [8].

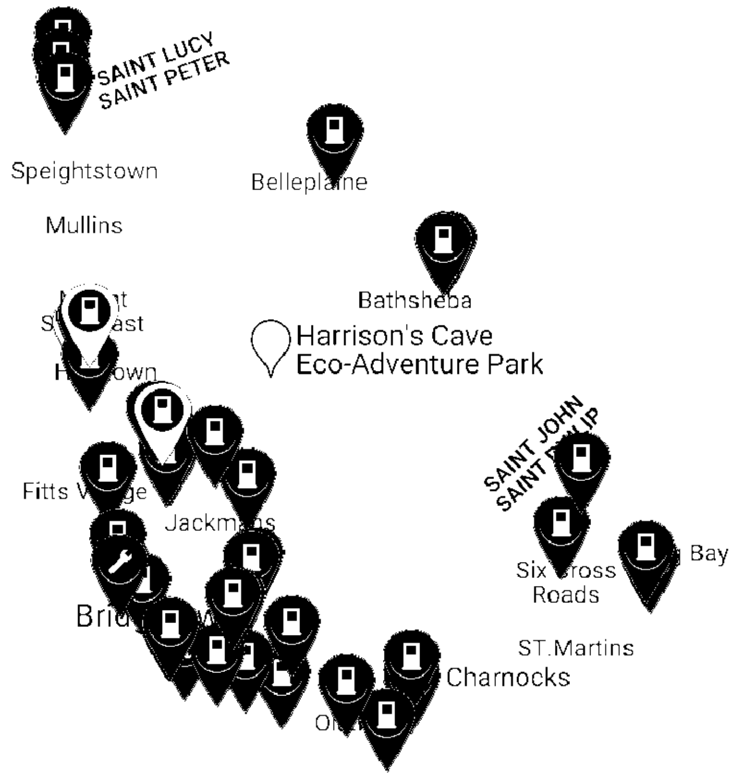


Figure 43: Barbados Charging Station Map

Source: Plugshare Website

The IRRP report estimated potential EV demand for road vehicles, based on several assumptions regarding their deployment and use. According to the report, electrical vehicles are evaluated in three key vehicle segments: light (LDV), medium (MDV), and heavy-duty vehicles (HDV). LDVs comprise predominantly private cars, while HDV comprises trucks and buses, with MDV comprising vans, small trucks, and minivans. The fleet numbers are taken from the IRRP Report [2].

The total annual potential consumption comes to 455 GWh by 2040, which is a little less than half the current annual electricity use across all sectors. This shows the potential EV consumption is reasonable given that an EV is typically 3-4 times as efficient as the comparable internal combustion engine vehicle.

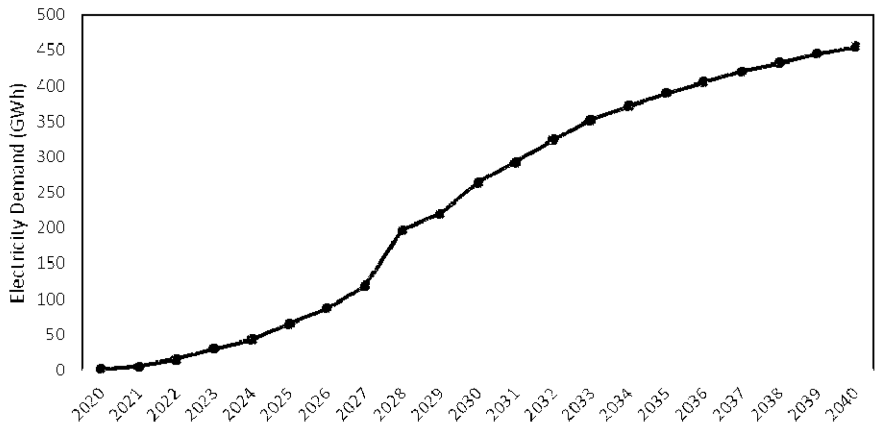


Figure 44: Projected EV Electricity Demand in Base Scenario

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

The projected EV electricity demand for each type of vehicle in the three scenarios is presented in Figure 45, with the LDVs having significantly higher demand than MDVs and HDVs.

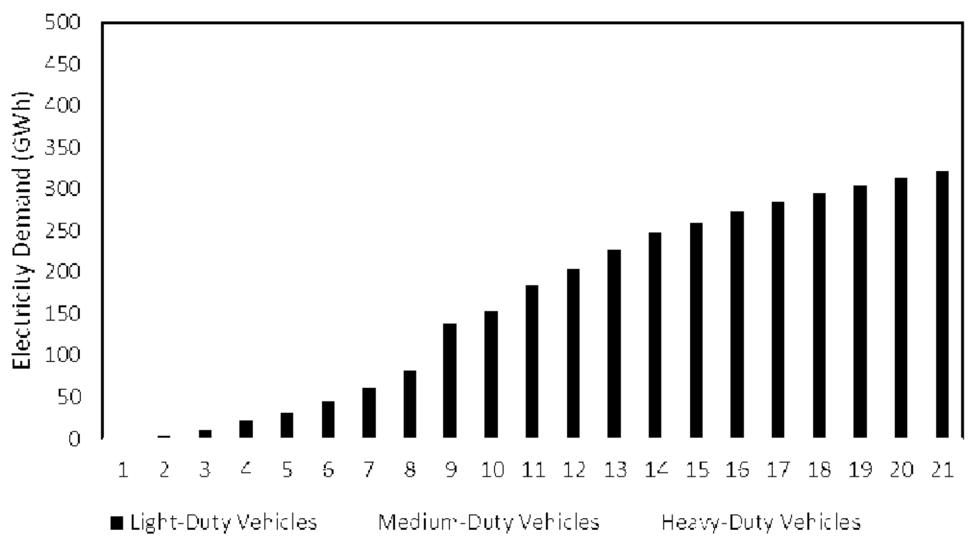


Figure 45: Projected EV Electricity Demand by Vehicle Type in Base Scenario

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

10.5 The Clean Energy Bridge Project

The Barbados Light & Power Company (BLPC) shows its commitment to 100% renewable energy in Barbados through its 100/100 vision. The Clean Energy Bridge is a 33 MW medium-speed diesel generation plant being constructed in St. Lucy – the heart of our renewable energy projects and the launchpad for the transition to 100% renewable energy. The Clean Energy Bridge (CEB) will allow BLPC to secure reliable baseload generation while they transition the current generation mix to a cleaner solution. More specifically, this CEB project:

- Provides reliable generation capacity while lowering the fuel bill and associated customer tariff;
- Provides Barbados with diverse asset management plan options (reduce the demand on older generation assets); and
- Overall, reduces energy costs for everyone.

10.6 Barbados IRRP Review

This section investigates the demand forecast, the scenarios that are defined in Integrated Resources and Resiliency Plan (IRRP) report, installed capacity and generation mix results, and fuel cost forecast. The LINDA model used in the IRRP is an Excel-based modeling tool that forecasts electricity demand by The Ministry of Energy, Small Business, and Entrepreneurship (MESBE).

10.6.1.1 Demand Forecast

The LINDA demand forecast model is used while forecasting Barbados' annual demand. According to the model, the demand is divided into different sectors, namely, commercial, hotels and restaurants, industry, residential, and transportation sectors. The potential range of demand is illustrated in Figure 46. It should be noted that the deviation from the reference scenario is between 67% and -34%. The extreme cases are evaluated as 3 different scenarios which are explained in the following subsection.

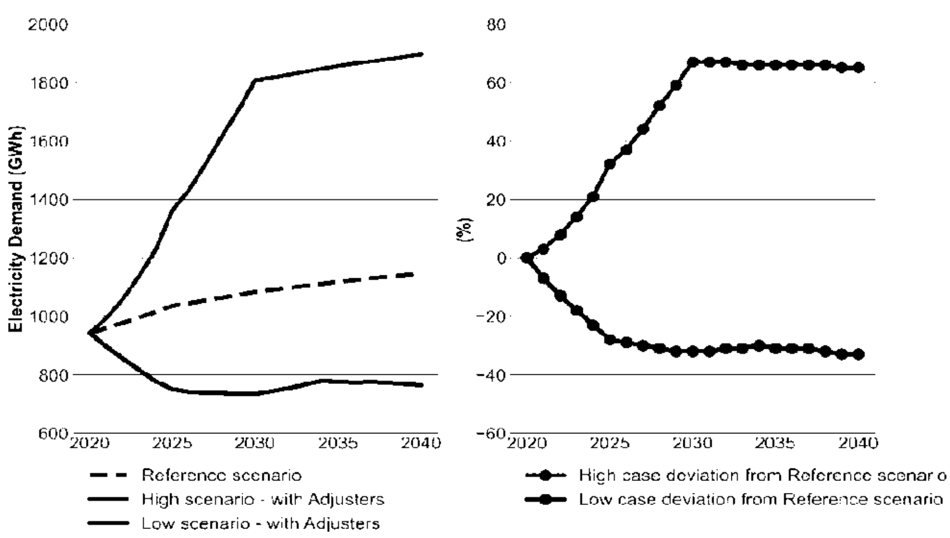


Figure 46: Potential range of demand scenarios (extreme cases)

Source: Integrated Resource & Resiliency Plan for Barbados

10.6.1.2 Scenarios

There are three demand forecast scenarios: base scenario, high scenario, and low scenario. All scenarios have a common base underlying reference demand scenario provided by MESBE in the LINDA model, combined with different adjustments provided in Table 27: Adjustment Table of Scenarios.

Table 27: Adjustment Table of Scenarios

Demand Scenario	Components of the demand scenario
Base Scenario	• Addition of base EV projection – which has 60% EV market share by 2030, with 50% smart charging and 50% fixed profile charging • Addition of base CL demand – six ships – 50% conversion by 2030 • Additions of base cooking demand • Deduction of base case DSM/EE savings.
High Scenario	• Addition of high (aggressive) case projection of EV demand - 100% EV share in 2030, with 100% smart charging • Addition of base CL demand – six ships – 50% conversion by 2030 Additions of base cooking demand • Deduction of base case DSM/EE savings.
Low Scenario	• Addition of low case projection of EV demand - 30% EV share in 2030, with 50% smart charging and 50% fixed profile charging • Addition of base CL demand – six ships – 50% conversion by 2030 Additions of base cooking demand • Deduction of base case DSM/EE savings.

Source: Integrated Resource & Resiliency Plan for Barbados

The projected energy demand of all scenarios is demonstrated in Figure 47. It is possible to examine the effects of the sectors on the demand.

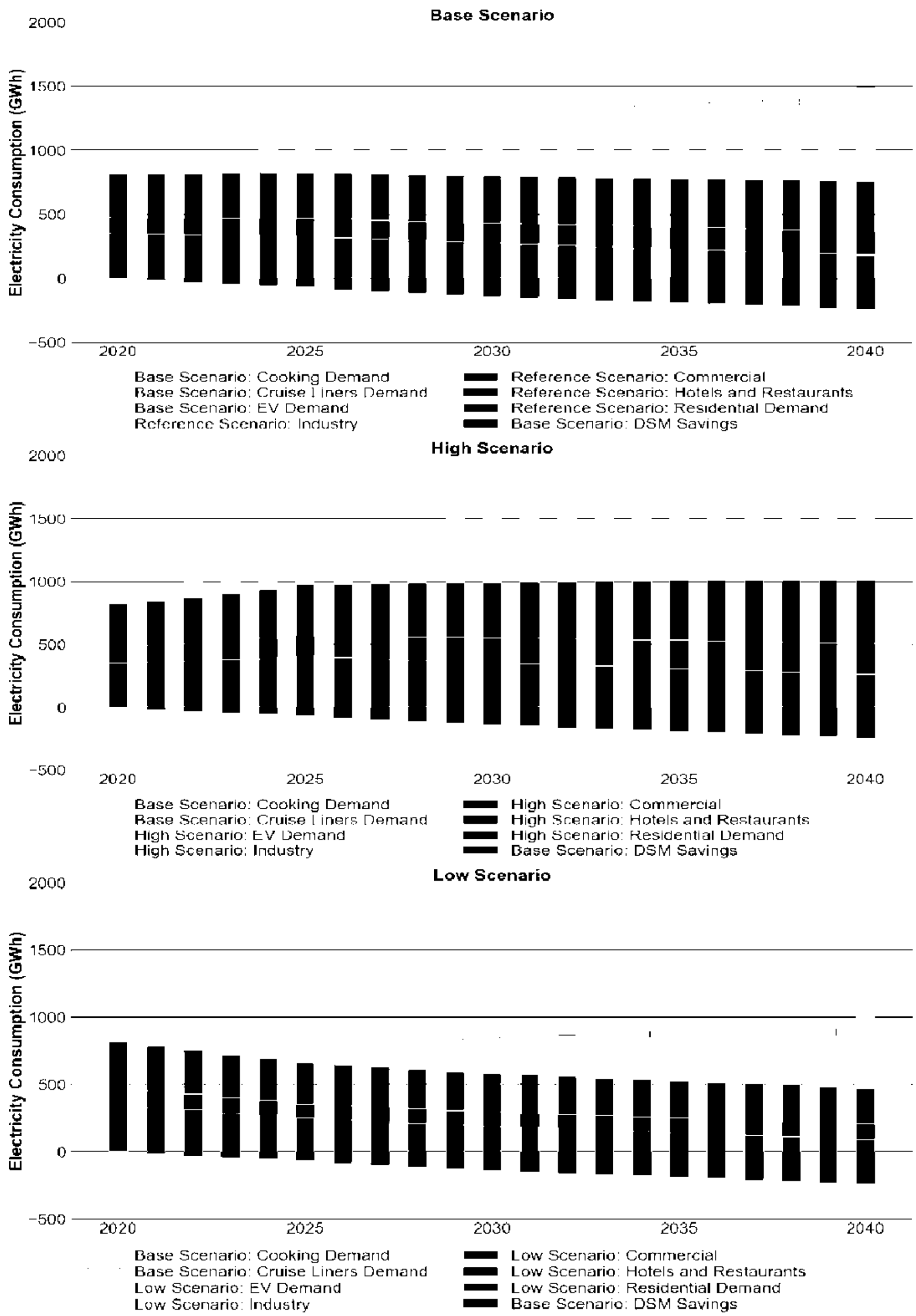


Figure 47: Projected electricity demand in the Base, High, and Low scenarios by sector

Source: Integrated Resource & Resiliency Plan for Barbados

10.6.1.3 Installed Capacity Results

The capacity expansion and retirements, investment and operating costs, generation mix, and typical dispatch analysis and curtailment, reliability, and operating constraints are analyzed in three different scenarios. There are different installed capacity results for each scenario that are illustrated in the following figures. The figures present the total installed capacity in terms of MW, capacity reserve margin as a percentage, and peak load (MW) between the years 2021 and 2030. The generation types can be summarized as Diesel, HFO, Jet, Solar, Solar Rooftop, Solar Thermal, Wind, and Biofuel. Moreover, battery contribution is also illustrated in the figures.

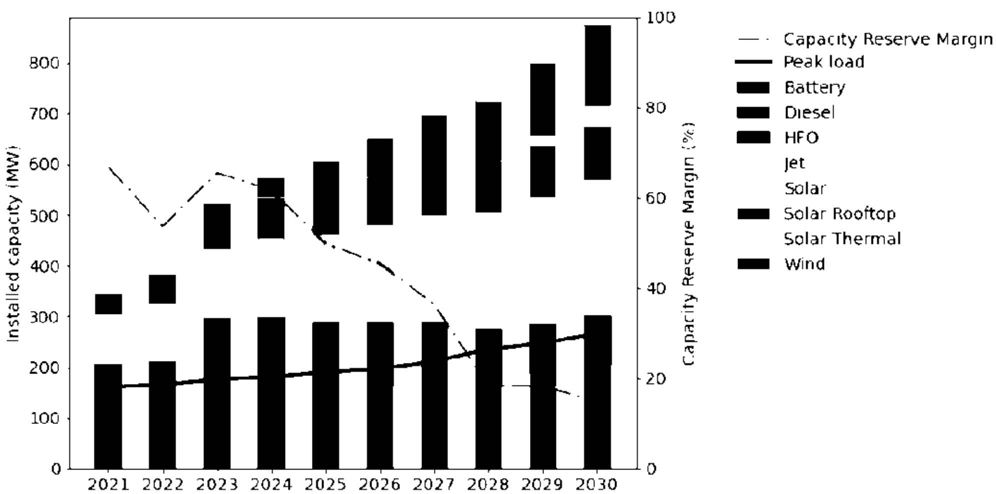


Figure 48: Scenario 1 – Installed capacity mix and peak load

Source: Integrated Resource & Resiliency Plan for Barbados

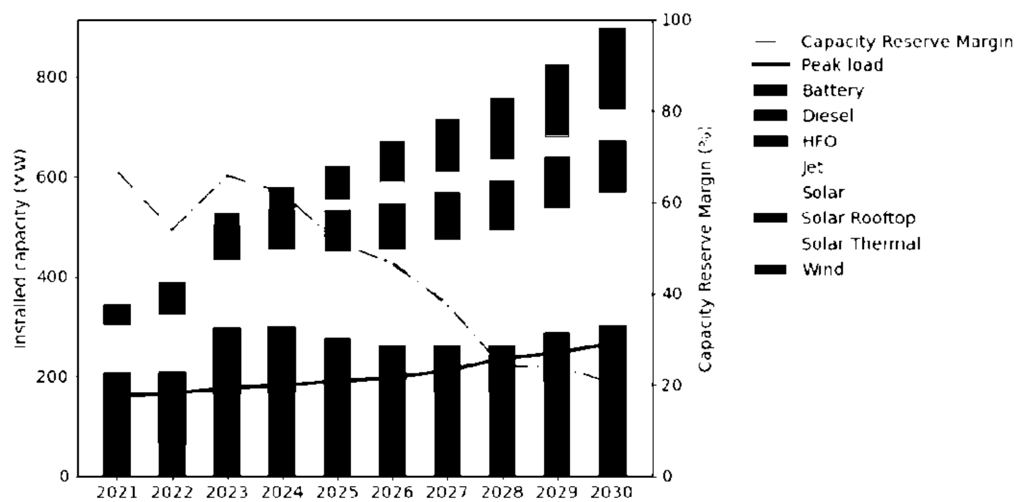


Figure 49: Scenario 2 – Installed capacity mix and peak load

Source: Integrated Resource & Resiliency Plan for Barbados

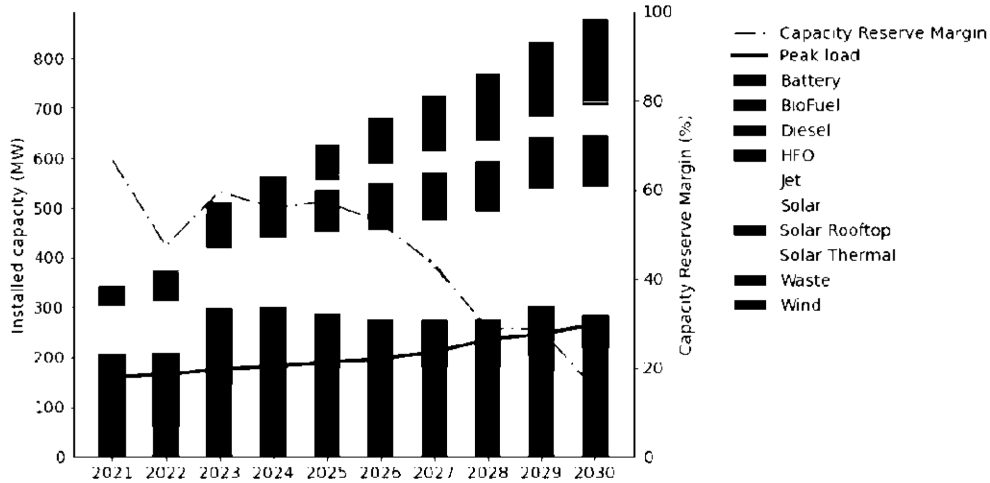


Figure 50: Scenario 3 – Installed capacity mix and peak load

Source: Integrated Resource & Resiliency Plan for Barbados

10.6.1.4 Generation Mix Results

The generation mix compared to the native and system load for each year [in GWh] is illustrated in the following figures. Normal electricity demand in Barbados is labeled as Native Load in the figures. Purchaser load refers to new demand sectors of demand that are expected to gradually electrify, such as EV and cruise liner demand. The dotted red line refers to the total demand that needs to be provided.

The ratio of fossil fuel to renewables generation rapidly inverts, even in Scenario 1 (see Figure 51), and by 2030 to only 9% of generation is from liquid fossil fuels, 41% from solar PV (ground-mounted and rooftop), 11% from CSP and 30% from wind. Battery generation is equivalent to 9% however that is not a net contribution since battery storage has a negative net generation due to charging losses.

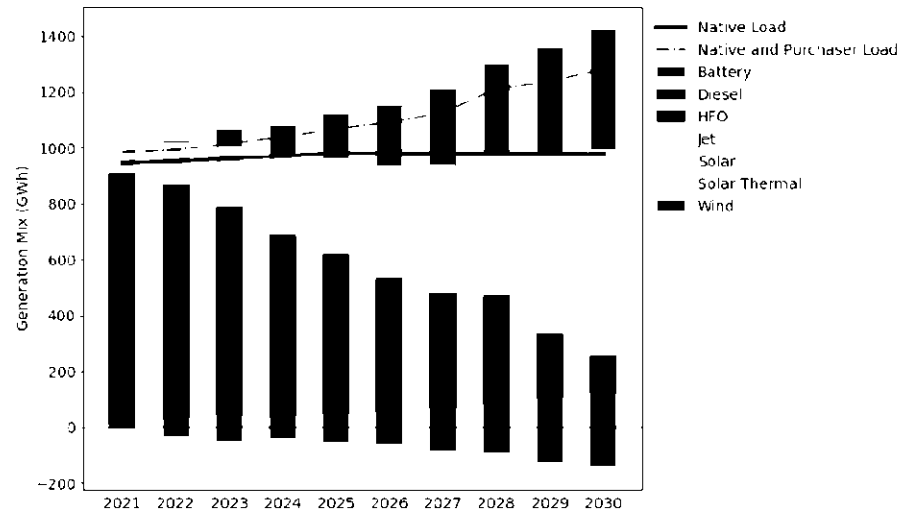


Figure 51: Scenario 1 – Generation mix

Source: Integrated Resource & Resiliency Plan for Barbados

The generation mix for Scenario 2 is shown in Figure 52, due to the more rapid uptake of renewables in this Scenario, the generation mix shifts even the 2030 generation mix is only 5% fossil fuels, 31% wind, 38% solar PV, 17% CSP, and 9% BESS. Fossil fuel generation is 4% less in this scenario than Scenario 1 due to additional CSP capacity.

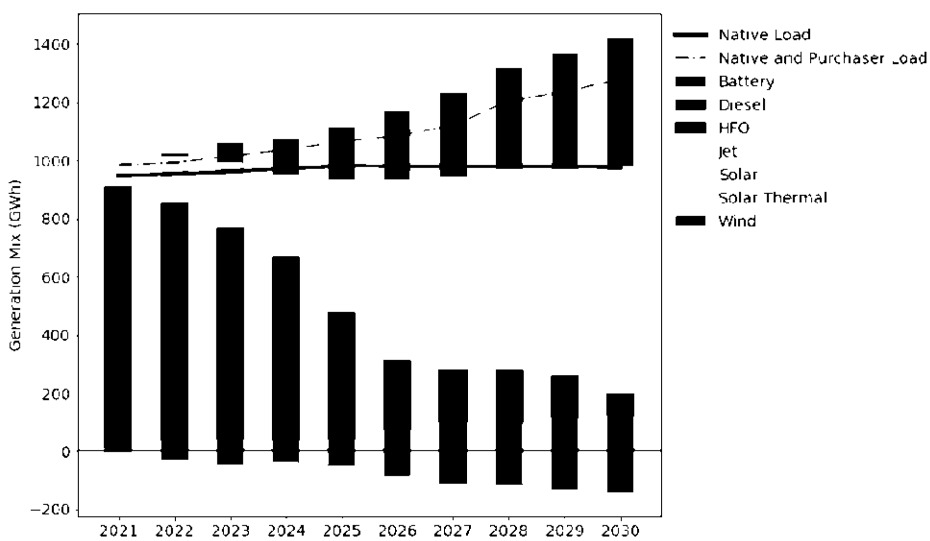


Figure 52: Scenario 2 – Generation mix

Source: Integrated Resource & Resiliency Plan for Barbados

Figure 7.18 below shows the generation mix for Scenario 3 which is slightly different due to the introduction of waste and biofuel plants from 2025. By 2030 the generation mix is 2% fossil fuels, 4 % firm renewables (waste – 1%, biodiesel – 3%), 31% wind, 38% solar PV, 14% CSP, and 9% BESS. Fossil fuel generation is 7% less than Scenario 1 and 3% less than Scenario 2.

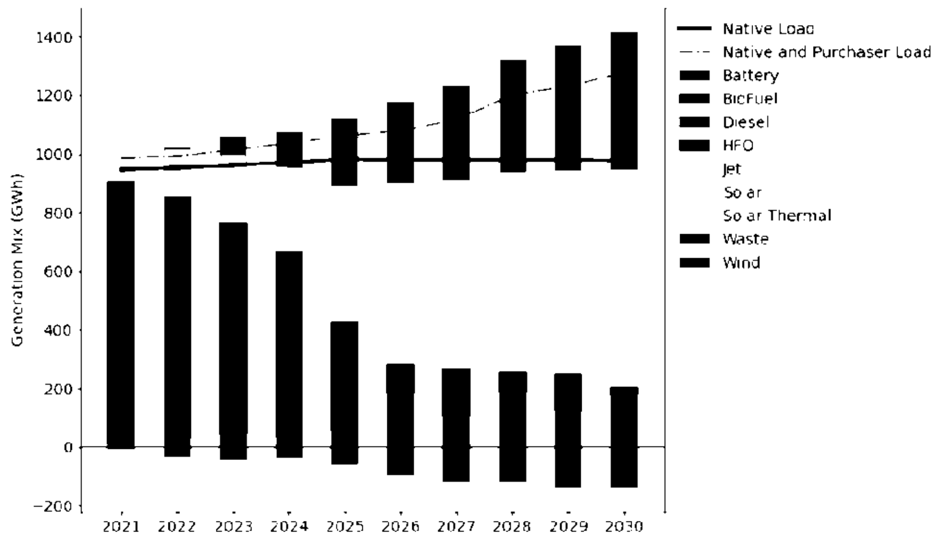


Figure 53: Scenario 3 – Generation mix

Source: Integrated Resource & Resiliency Plan for Barbados

10.6.1.5 Fuel Cost Forecast

The main fuel categories are conventional fossil fuels (HFO, Jet A1, and Diesel) and bio-sourced fuels (Biomass, Land Gas, and Biodiesel) in the IRRP report. The price reference for the fossil fuel's prices was set by the latest Energy Information Administration (EIA) forecast issued in February 2021 from the US Department of Energy (DOE). The fuel price projections are illustrated in Figure 54.

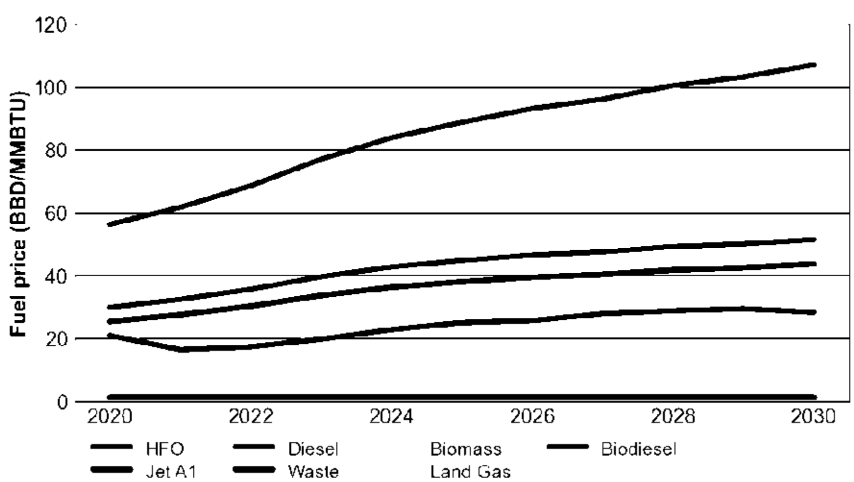


Figure 54: Base fuel price projections 2020-2030

Source: Integrated Resource & Resiliency Plan for Barbados based on EIA's January 2021 annual energy outlook

11. Appendix-B: Input Data and Forecasts

This section explains the source and forecast methods of the data used by Acelerex during the analysis. Demand profile, peak load, and annual energy demand data are explained below. Fuel prices and forecast methods are provided in Fuel Price Forecasts. The total installed capacities over time and renewable capacities are discussed in Installed Capacity by Fuel Type. The parameters of the present generators are provided. Solar and wind profiles that are used in the Acelerex simulation are illustrated in

Renewable Generation Profile. The retirement schedule of the generators is explained in the Expansion and Retirement Schedule. Lastly, the carbon dioxide emission price is explained in the Emission Price Forecast section.

11.1 Demand Profile

Hourly demand profile between 2017 and 2020 is provided by the BLPC. The hourly demand profile being used in the simulation is created by the average methodology of four historical years. The blackouts and brownouts that were observed are excluded from the calculations. The full year and a typical week hourly demand curve are illustrated in Figure 55.

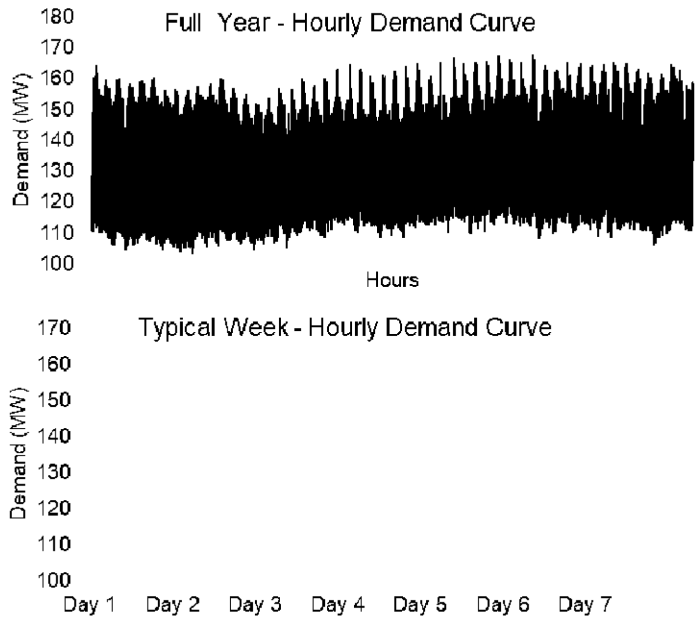


Figure 55: Typical Week – Full Year Hourly Demand Curve

Chart: Acelerex

11.2 Annual Peak Load and Energy Demand Forecast

The annual peak load and the annual energy demand data are received from the IRRP Report [2] for the years between 2022 and 2030. There are two different peak load values on the IRRP Report. Figure and Table of the figure have different values. The peak load is received from the figure. Energy demand and peak load inputs are illustrated in Figure 56. A significant portion of the load in future years is expected from electric vehicles.

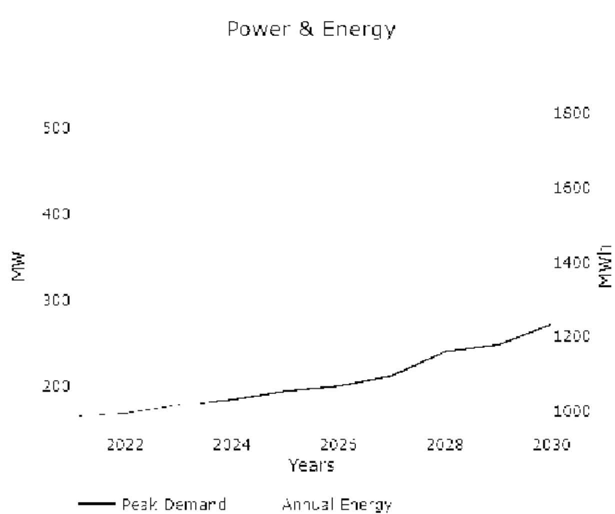


Figure 56: Peak Demand & Annual Energy

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

11.3 Fuel Price Forecasts

For this study following 6 fuel types are used: HFO (Heavy Fuel Oil), Jet A1, Diesel, Landfill, Biomass, and Waste. The prices are given in BBD. Therefore, fuel prices are converted to USD with a 2.02 exchange rate. The estimation between 2022 and 2030 is received from the IRRP Report [2]. Fuel price forecasts in USD are given in Figure 57.

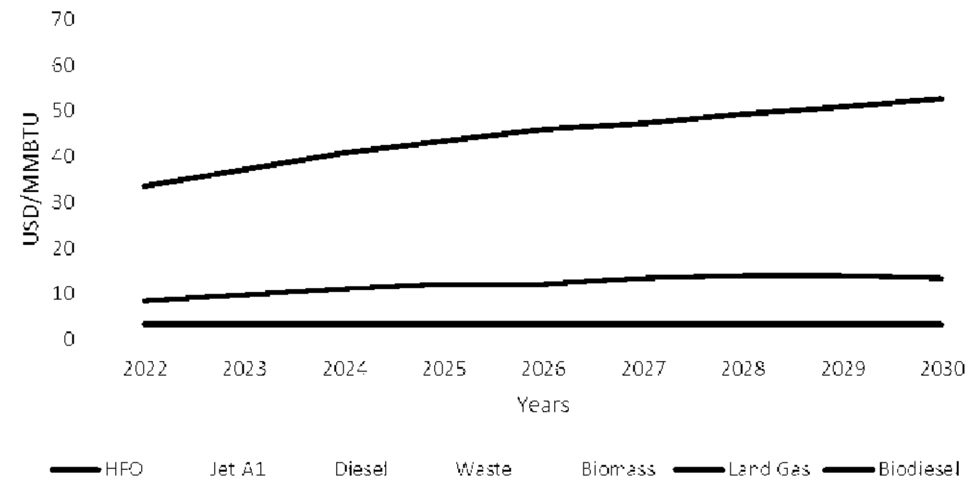


Figure 57: Fuel price projections 2022-2030

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

11.4 Installed Capacity by Fuel Type

Existing generators and their installed capacities are explained in Generation Capacity. The generation capacity by fuel type between 2022 and 2030 is illustrated in Figure 58.

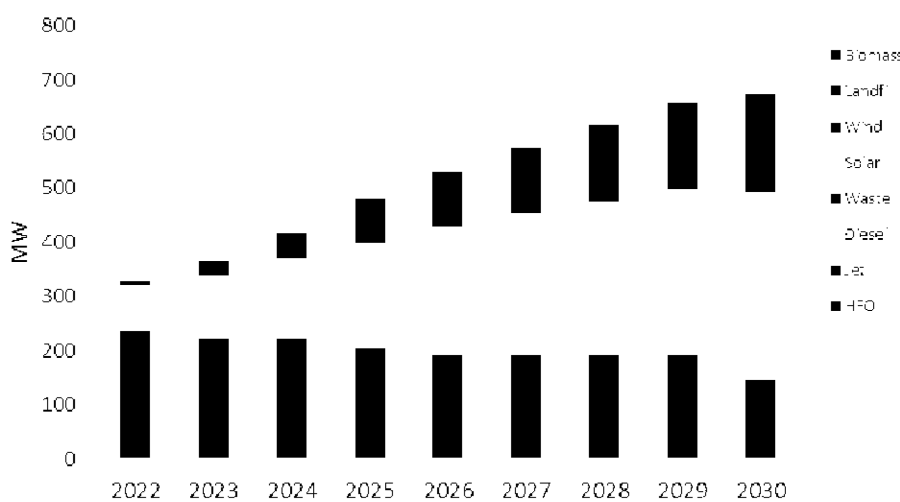


Figure 58: Installed Capacity by Fuel Type (Scenario 3 in IRRP)

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

The installed capacity by fuel type over years is given in Table 28. The values in the table between 2022 and 2030 are represented in Figure 58.

Table 28: Installed Capacity (MW) by Fuel Type

Fuel Type	2022	2023	2024	2025	2026	2027	2028	2029	2030
HFO	162	149	149	124	111	111	111	111	65
Jet fuel	73	73	73	73	73	73	73	73	73
Diesel	0	0	0	0	0	0	0	0	0
Landfill	0	0	0	5	5	5	5	5	5
Bio-mass	0	0	0	10	10	10	10	10	10
Wind	6	26	46	66	86	106	126	146	166
Solar	86	118	147	193	238	262	284	306	346
Energy Storage	48	148	150	150	150	150	151	175	204

11.5 Renewable Capacity

Solar installed capacity is illustrated in Figure 59. Additions and retirements are referred from the IRRP Report [2]. Solar installed generation increases from ~51 MW to ~325 MW until 2030. Furthermore, the firm power of the solar generation is assumed as 20%.

Figure 59: Installed Solar Capacity by Generator

Source: Integrated Resource & Resiliency Plan for Barbados, Acelerex, Chart: Acelerex

Total wind installation capacity is illustrated in Figure 60. The installed capacity increases by 20 MW per year starting from 2023. There is no retirement due to the horizon of the study. Moreover, the firm power of the wind generation is presumed as 30%.

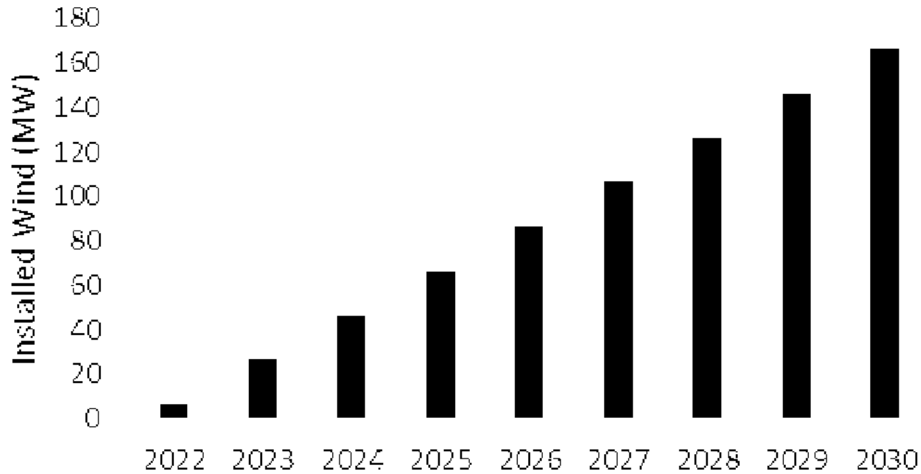


Figure 60: Installed Wind Capacity

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

Table 29 below presents key information on the existing units as presented in the Barbados Acelerex model obtained from IRRP Report [2]. The key information can be listed as installed capacity [MW], technical life [years], resource begin operation year (start year) [years], ramp rate[MW/h], heat rate[GJ/MWh], emission rate [ton/GJ], firm power(availability rate) [%], variable operation & management costs[$/MWh], fixed operation & management costs[$/kW-years].

Table 29: Generator Details

Source: Integrated Resource & Resiliency Plan for Barbados, Acelerex

[redacted]

[redacted]

11.6 Renewable Generation Profiles

The annual hourly solar profile is prepared by the solar profiles received from MESBE between 2017 and 2020. The average of the years between 2017 and 2020, excluded errors, is used as the solar profile. The representative solar profile for a 1MW solar PV plant with no tracking system is shown in Figure 61. The excluded errors include outages, missing and repeating values.

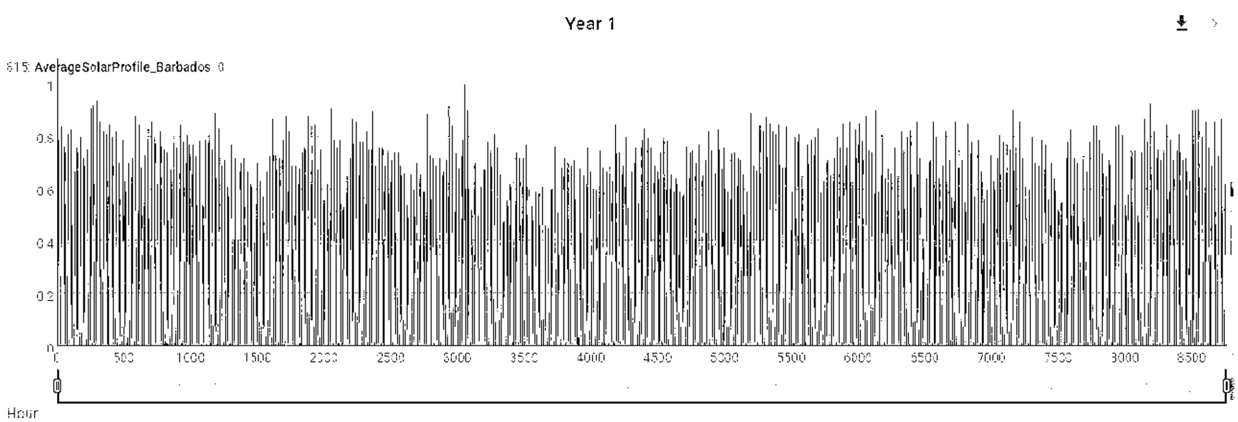


Figure 61: Annual Hourly Average Solar Profile of Barbados

Source: MESBE, Chart: Acelerex Software

The annual hourly wind profile is received from the renewables ninjas website [9]. The representative wind profile for a 1MW representative turbine with 80 meters hub height is shown in Figure 62. Wind profile is continuous unlike solar profile; therefore, average capacity factors are significantly different: solar has a capacity factor of 20.49% and wind has a capacity factor of 36.36%.

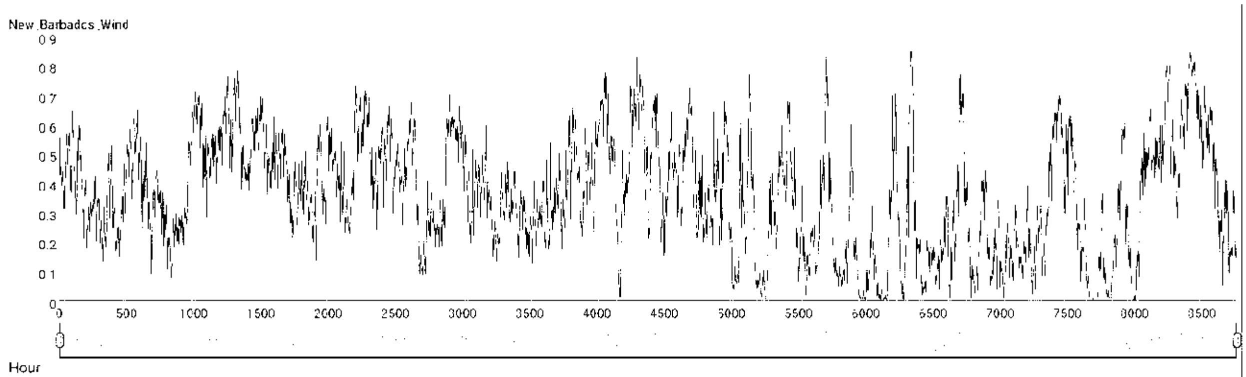


Figure 62: Annual Hourly Wind Profile of Barbados

Source: Renewables Ninja, Chart: Acelerex Software

11.7 Expansion and Retirement Schedule

Expansions and retirements by generator between 2022 and 2030 are illustrated in Figure 63. Expansions, the schedule is received from the IRRP Report [7]. The general trend is building more renewable generators while retiring thermal generators that are using fossil fuels. 3 new generators are built in 2025; landfill, biomass, and waste. The positive capacity in the figure indicates an expansion but the negative capacity in the figure indicates the retirement at that year.

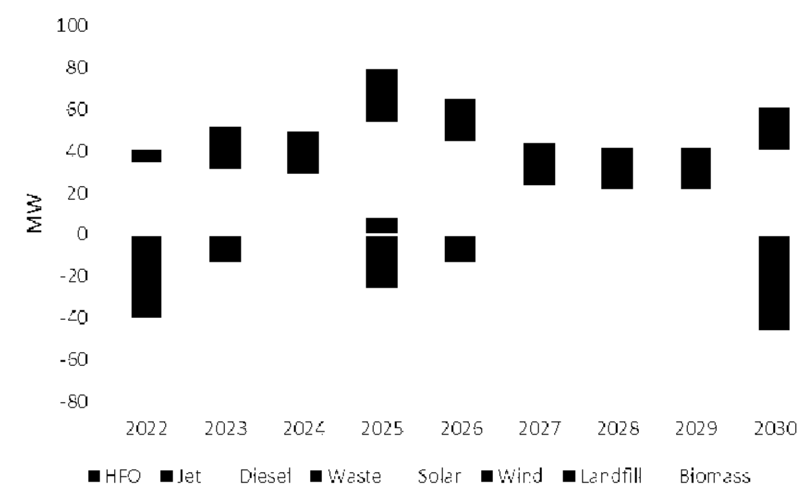


Figure 63: Expansions and Retirements of Barbados

Source: Scenario 3 in Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

11.8 Emission Price Forecast

A carbon price starting at ~80 USD/tCO_2 in 2022 and increasing up to 100 USD/tCO_2 in 2030, see Figure 64. The IRRP Report emission price is used with the linear incrementation technique. It should be noted that the unit for the emission is tonne which is 1,000 kg.

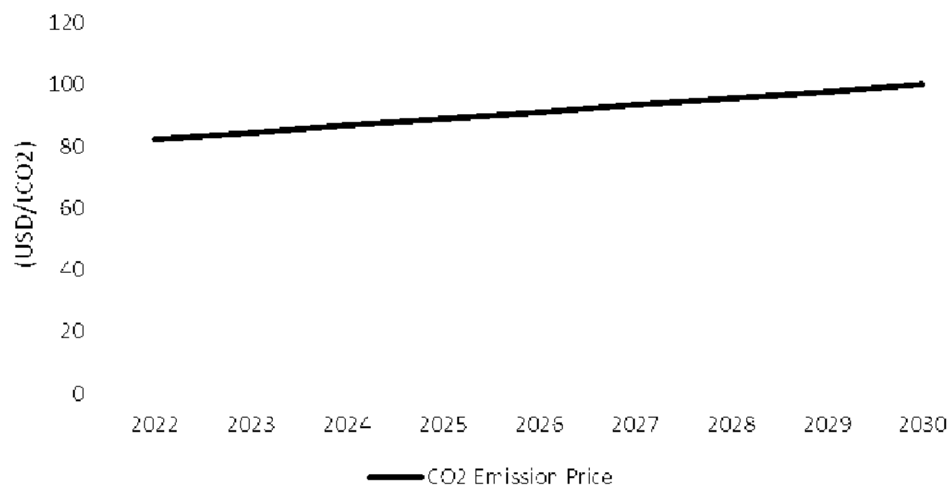


Figure 64: Emission Price per tonne

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

11.9 Technology Assumptions

This section presents the technology assumptions that are used in the study. Technology assumptions include general, base case, expansion, energy storage build cost, energy arbitrage analysis with price data, energy storage parameters, and economic life assumptions.

11.9.1.1 General Assumptions

General assumptions, descriptions, and values are listed in Table 30. The discount rate is assumed as 2%. Moreover, the currency exchange of 2.02 BBD/USD is assumed throughout the study.

Table 30: General Assumptions

Assumption	Description	Value
Discount Rate	The discount rate applies to all cash flows over the study horizon and is used to calculate the NPV of these cash flows.	2%
Currency	Acelerex executes economic analysis in USD currency. All BBD values are converted in USD.	1 USD = 2.02 BBD

11.9.1.2 Base Case Assumptions

Base case assumptions include renewable and thermal additions, energy demand growth rates, fuel price forecasts, retirement schedules, and economic builds. The base case study is based on the inputs and assumptions in Table 31.

Table 31: Base Case Inputs and Assumptions

Inputs and Assumptions	Details
Peak Load	IRRP 2021 (based on the figure, not the tables)
Annual Energy Demand	IRRP 2021 (Projected final electricity demand Base Scenario)
Hourly Demand Profile	Hourly total BLPC load 2017-2020
Solar Profile	Trents 10MW Solar Power Plant 2017-2020 hourly average excluding outliers
Wind Profile	Renewables.ninja, Hourly generation for Barbados
Solar and Wind Capital Costs	IRRP Capital Cost (2020) & Cost Decay per Year
Oil, Diesel, Jet, Waste Fuel Prices	IRRP 2021
Thermal Generator Retirements	IRRP 2021: Scenario 3
Thermal Generator Additions	IRRP 2021: Scenario 3 * Clean Energy Bridge project
Carbon Pricing	IRRP 2021

11.9.1.3 Expansion Generators

For the capacity expansion planning phase, this study considers new economic expansion for technologies such as energy storage, wind generators, and solar PV. When a generator becomes financially viable it will be added to the system to meet the demand. Indicative assumptions for average heat rates, emission rates, technical life, minimum capacity are shown in Table 32. These assumptions are made based on the data collected from the IRRP report.

Table 32: Expansion Generator Properties Assumptions

Unit Name	Type	Technical Life (Years)	Firm Power (%)
Solar Utility	Solar PV	25	20 %
Wind	Wind Power Generator	20	35 %

Indicative assumptions for capital cost, variable operation and maintenance charges, and fixed operation and maintenance charges are detailed in Table 33. The capital investment cost figures are received from the Barbados IRRP in BBD but converted to USD to be consistent with the other figures in the report. The Fixed O&M figures for solar and wind are indicative assumptions compiled from several resources. Specific projects may have different figures based on the breakdown of security & maintenance costs, overhead costs, insurance, liability & provisioning costs, land cost, depreciation costs, augmentation costs, etc.

Table 33: Expansion Generator Cost Assumptions

Unit Name	Type	Capital Investment Cost (2020$/kW)	Variable O&M ($/MWh)	Fixed O&M ($/kW-y)
PV (Ground Mounted)	Solar PV	3,121BBD* = USD1,545	-	18
Wind	Wind Power Generator	4,208 BBD* = USD2,083	-	40

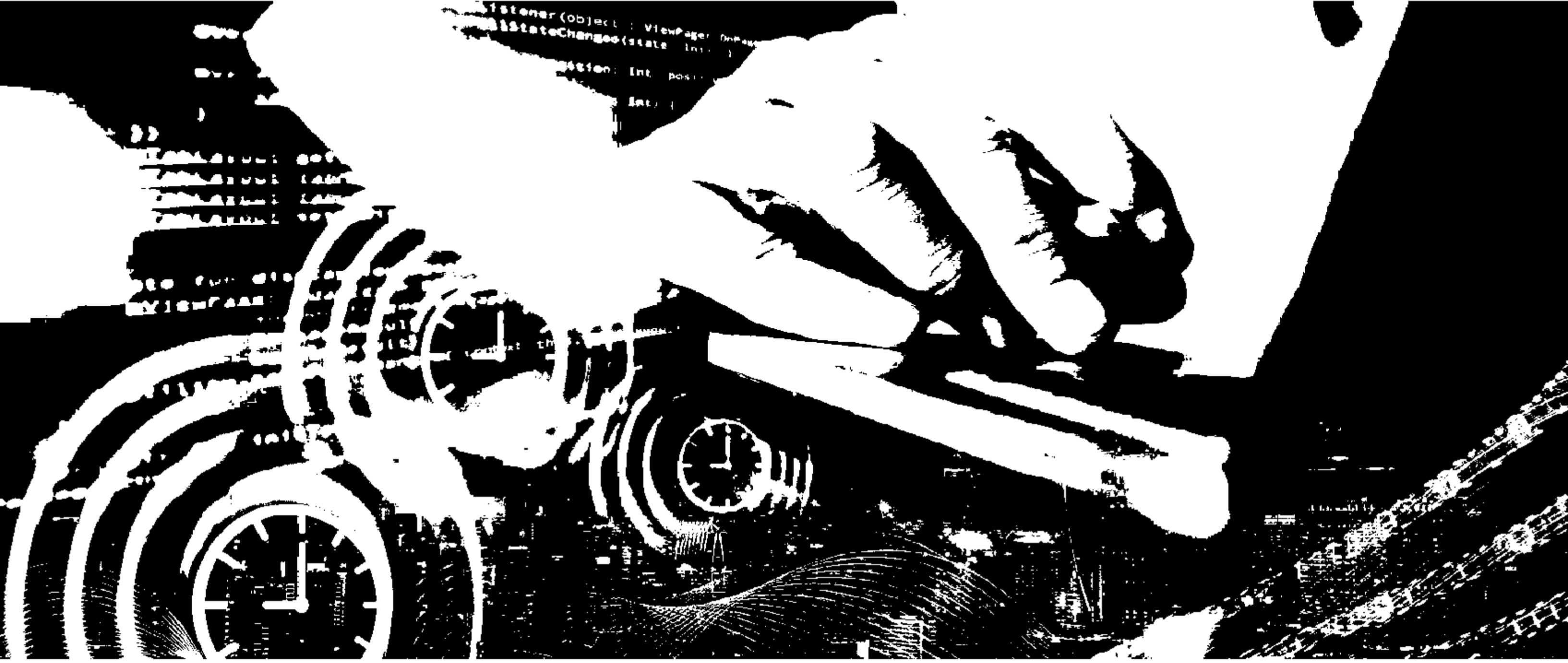
* BBD values are received from IRRP. Source: Integrated Resource & Resiliency Plan for Barbados, Acelerex

11.9.1.4 Energy Storage Parameters

The assumptions of energy storage parameters are given in the table below.

Table 34: Energy Storage Parameters

Data	Details
Fixed operational and maintenance charge ($/kW-year)	$6/kW-y
Variable operational and maintenance charge ($/kW-year)	$0/kW-y
Firm Power (%)	25% for 3h and 4h systems
Round-trip energy efficiency (%)	87%
Lifespan	Minimum 10 years



12. Appendix-C: Benchmark

This section compares the results of the Acelerex model and the Barbados IRRP Report in terms of peak and annual energy demand, generation installed capacity, energy by fuel type, capacity factors, typical week dispatch, annual fixed O&M, and average fuel prices. The time horizon of the benchmarking is 2021-2030.

12.1 Peak Demand & Annual Energy Demand

The peak load and annual energy demand data series that are received from the IRRP Report [2] are illustrated in Figure 65. Peak load is presented by blue columns starting from ~164 MW in 2021 and growing gradually up to ~272 MW in 2030. Furthermore, the annual energy demand increases up to ~1,370 GWh in 2030.

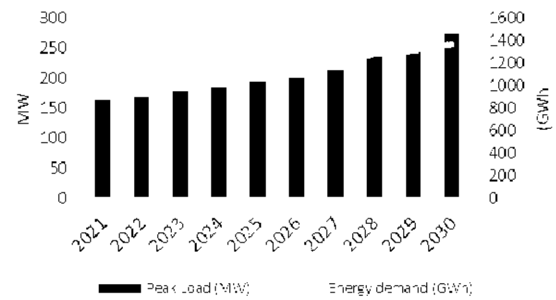


Figure 65: IRRP Peak Load & Energy Demand

Source: Integrated Resource & Resiliency Plan for Barbados, Chart: Acelerex

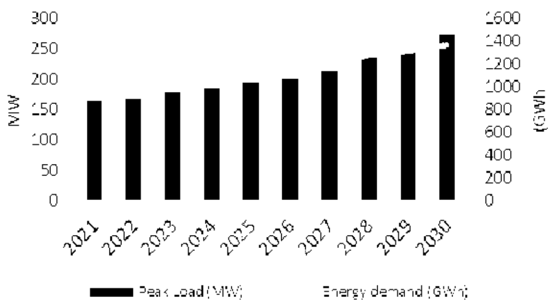


Figure 66: Acelerex Model Peak Load & Energy Demand

Source: Acelerex

12.2 Installed Capacity

The installed capacity of a generator is the maximum output of electricity that a generator can produce under ideal conditions. The installed capacity is generally measured in megawatts (MW). The installed capacity projection of Barbados by fuel type between 2021 and 2030 is shown in Figure 67 per Barbados IRRP Scenario 3. Fossil fuel capacities don't grow over time; however, renewable energy sources are growing significantly. The same installed capacity projection is considered in the Acelerex study as visualized in Figure 68

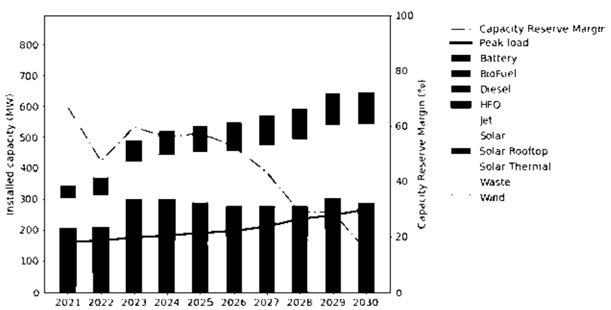


Figure 67: Installed Capacity by Year (IRRP)

Source: Integrated Resource & Resiliency Plan for Barbados

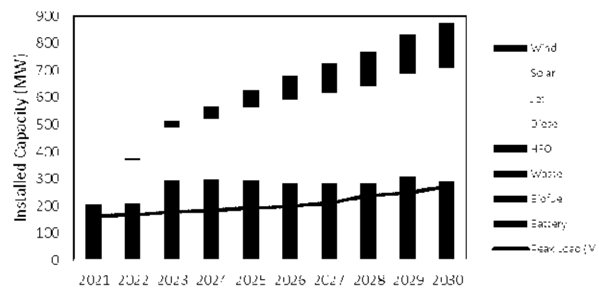


Figure 68: Installed Capacity by year (Acelerex Model)

Source: Acelerex

12.3 Energy by Fuel Type

Energy generation refers to the amount of electricity that is produced over a specific period. This is usually measured in kilowatt-hours, megawatt-hours, or gigawatt-hours (GWh). The generation mix as reported in IRRP is provided in Figure 69. According to the production cost simulation by Acelerex, the generation mix between 2021 and 2030 is illustrated in Figure 70 as well. In both results, the generation by HFO decreases while the renewable sources (solar and wind) penetrate most of the generation. It is noted that all solar energy systems referred to in the IRRP are aggregated in the Acelerex simulation as solar PV systems.

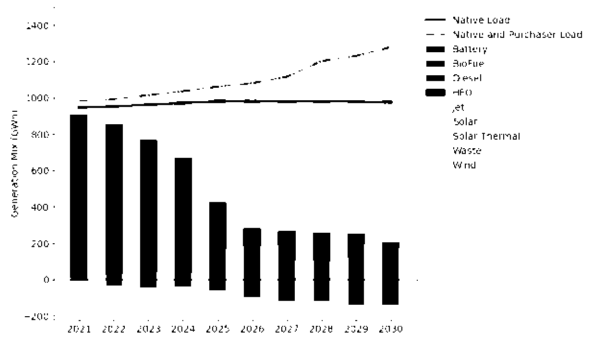


Figure 69: Generation Mix (IRRP)

Source: Integrated Resource & Resiliency Plan for Barbados

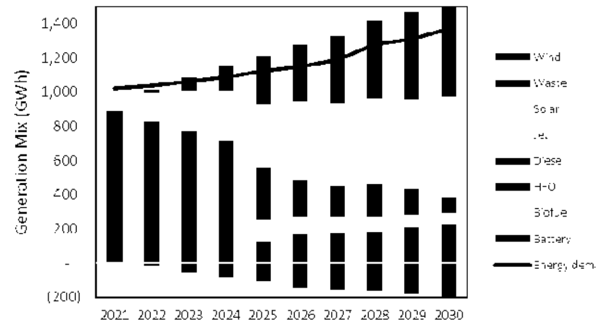


Figure 70: Generation Mix (Acelerex Model)

Source: Acelerex

12.4 Capacity Factors

The capacity factor is the unitless ratio of actual electrical energy output over a given period to the maximum possible electrical energy output over that period. The calculated capacity factors by fuel type are provided in Figure 71 and Figure 72 for the IRRP results and the Acelerex results respectively. It is noted that all solar energy systems referred to in the IRRP are aggregated in the Acelerex simulation as solar PV systems.

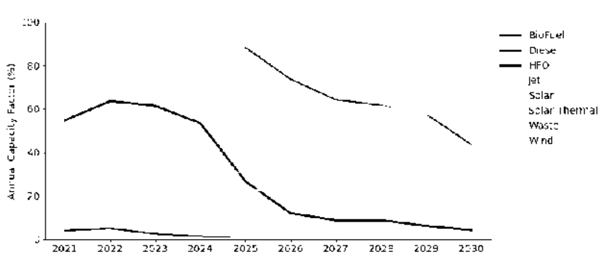


Figure 71: Capacity Factor by Fuel Type (IRRP)

Source: Integrated Resource & Resiliency Plan for Barbados

Figure 72: Capacity Factor by Fuel Type (Acelerex)

Source: Acelerex

12.5 Typical Week Generation Mix

The generation mix refers to the combination of the various fuels used to generate electricity in Barbados. Figure 73 is received from the IRRP that illustrated the generation mix by fuel type of scenario 3 in the IRRP report and Figure 74 shows the Acelerex production cost model results.

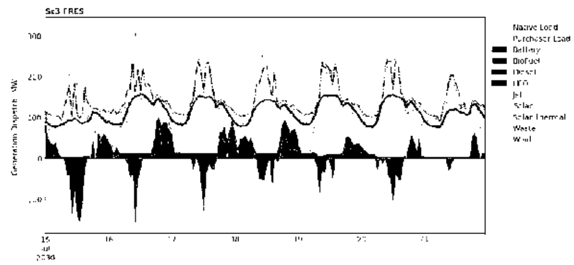


Figure 73: Typical Week Generation Mix (IRRP)

Source: Integrated Resource & Resiliency Plan for Barbados

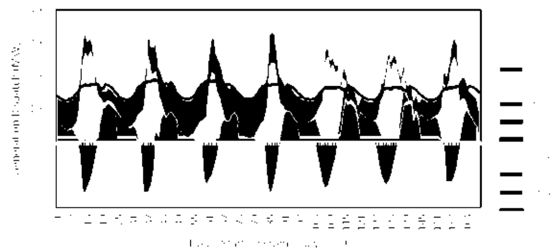


Figure 74: Typical Week Generation Mix (Acelerex)

Source: Acelerex

12.6 Annual Fixed O&M Costs

The fixed operation and maintenance cost is the recurring annual cost that includes general and administrative expenses regardless of electrical production. The comparison between Acelerex results and the IRRP report in terms of the annual fixed O&M costs is provided in Figure 75. The fixed cost is generally correlated with the installed capacity; therefore, we observe an increasing trend on the fixed O&M because of the growth in renewable installed capacity over the years.

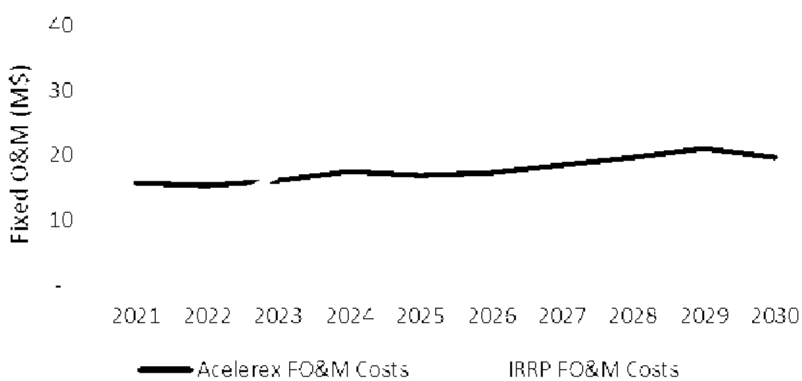


Figure 75: Annual Fixed O&M Costs (IRRP - Acelerex Model)

Source: Integrated Resource & Resiliency Plan for Barbados, Acelerex Chart: Acelerex

12.7 Annual Average Fuel Prices

The annual average fuel prices are received from the IRRP Report [2] in BBD and converted into USD/MMBTU by using the assumed currency exchange of 1 USD = 2.02 BBD. Fuel prices in terms of BBD are illustrated in the following figures, see Figure 76 and Figure 77.

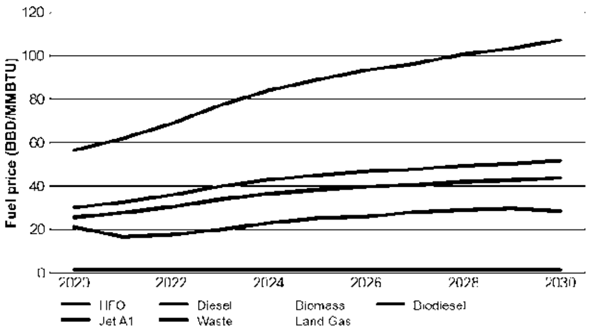


Figure 76: Fuel Price (IRRP)

Source: Integrated Resource & Resiliency Plan for Barbados

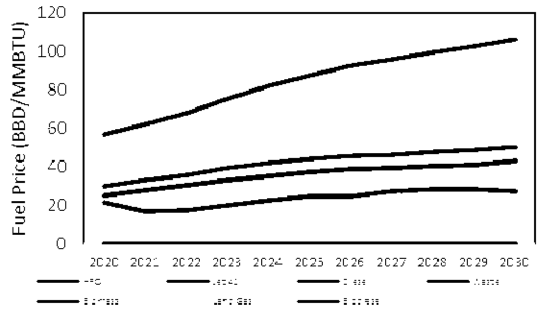
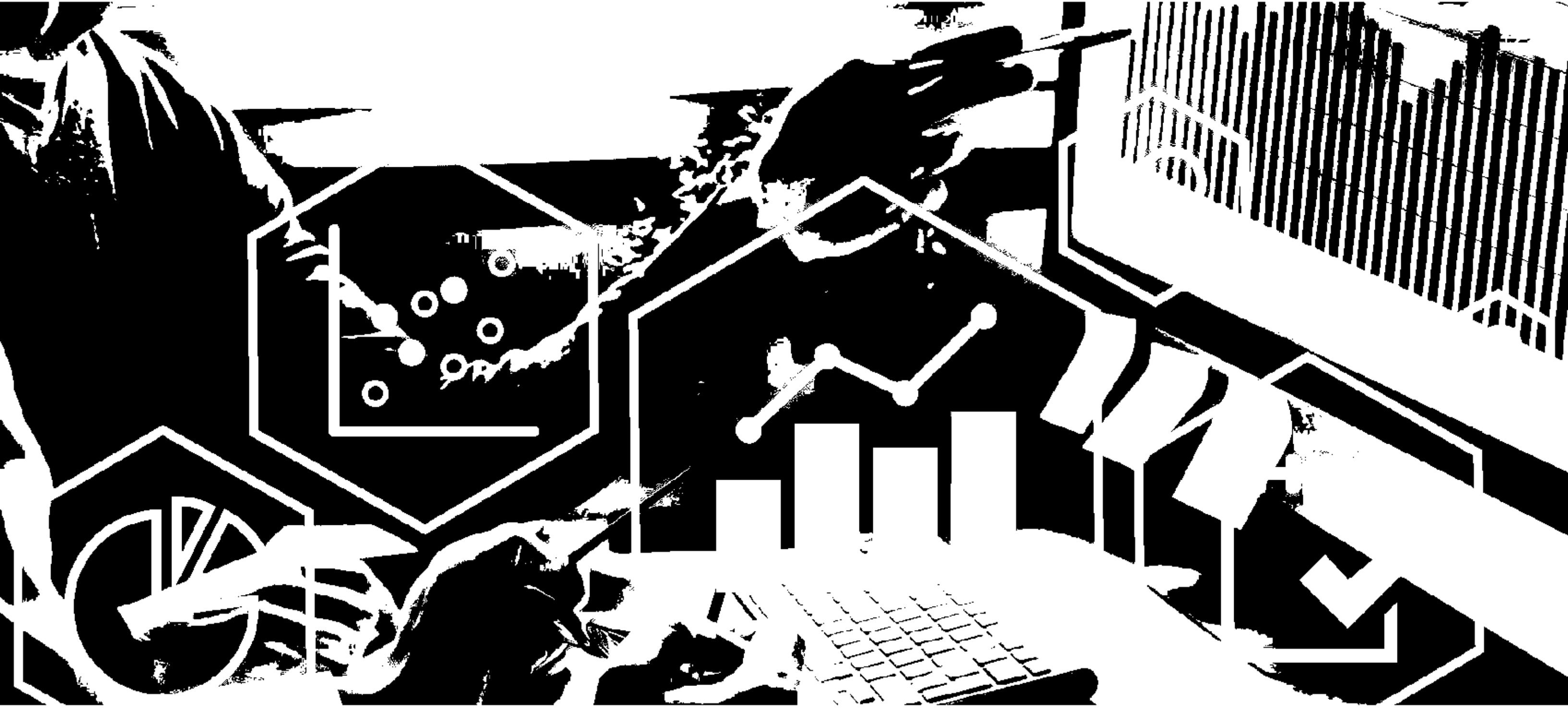


Figure 77: Fuel Price (Acelerex)

Source & Chart: Acelerex



13. Appendix-D: Methodology

In this section methodology overview, Acelerex proprietary grid analytics software, model overview, technologies considered, capacity optimization, production cost phase, Acelerex stacked services emulator (SSE), Valuation metrics, and net present value are discussed.

13.1 Methodology Overview

The study follows a three-step modeling approach to determine *when* and *how much* of the energy storage system should be implemented into the Barbados grid.

The Acelerex Analytics Software was used in this study for the capacity expansion model, production cost model, and stacked services model. The software solves for multi-year optimal capacity across all fuel, renewables, and storage types and returns optimal sizing of MW and MWh, hourly & sub-hourly optimal dispatch, and energy prices to quantify the economic value of adding energy storage to the grid. The software has various modules as seen in Figure 78, in which the Alternative Analysis (AA), Production Cost (PC), Emulators are used for this study.

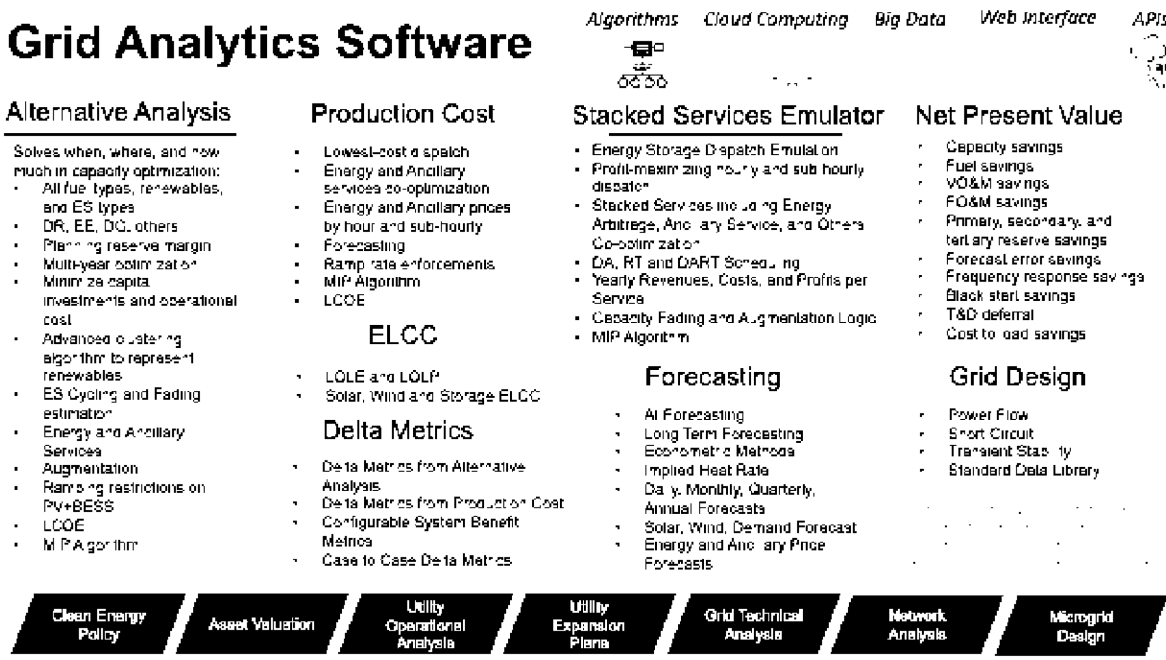


Figure 78: Acelerex Analytics Software

Source: Acelerex

13.2 Model Overview

The augmented model framework for planning future policies combines a capacity optimization (alternative analysis) phase with a production cost phase. By combining the capacity planning model and the production cost model, it is possible to do policy planning. This model was prepared to look at energy storage expansion and can be extended to be used for other types of technologies and technology evaluations or policy futures to investigate the combined impact of capacity expansion and short-run marginal cost. The modeling consists of three phases:

1. **Alternative Analysis**, to determine the expansion of storage and peaker plants
2. **Production Cost**, including Annual, Short-Term, and Real-Time Optimization, to determine the dispatch of the storage and peaker plants and associated prices
3. **Stacked Services Emulator** to model the provision of services by the energy storage

The modeling process overview is outlined in Figure 79. It shows that to perform alternative analysis modeling inputs such as capital costs, load growth, emission regulations, environmental regulations, fuel price forecasts, and base case model values are used. The results of alternative analysis guide the production cost calculations which are further used for valuation along with stacked services emulations. The study methodology is designed to be agnostic to energy storage technology assumption sets.

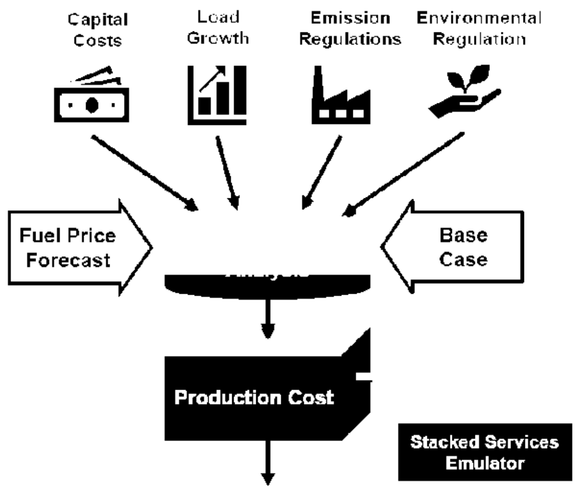


Figure 79: Model Overview
Source: Acelerex

13.3 Alternative Analysis Phase

The alternative analysis provides all reasonably plausible capacity optimization phase objects with inputs of capital costs and operational costs of current assets and future assets to run the grid, as well as new technologies assumptions, and performs cost minimization. The capacity optimization phase determines the MW / MWh size of energy storage and MW of generation technologies. The objective function of the capacity optimization modeling minimizes the production cost and the capital cost of the system. An annual optimization is performed over each year of the study horizon. The alternative analysis model objective function is based on the following equation.

Minimize [Sum of Capital Costs of Thermal Generators] + [Sum of Variable Costs of Thermal Generators] + [Investments in Energy Efficiency] + [Investments in Demand Response] + [Variable Demand Response Costs] + [Investments in VER] + [Investments in ESS for Power Capacity] + [Investments in ESS for Energy Capacity] + [Variable Costs of ESS for Power Output]

In the alternative analysis phase, expansion is allowed for Solar PV, wind, biofuel, waste, and energy storage (ES) technologies.

13.4 Production Cost Phase

The production cost (PC) phase is responsible for optimizing the dispatch of generators and energy storage units to find the lowest-cost system dispatch and corresponding energy prices for the hourly market. The PC phase adheres to system constraints including minimum ramp up and down times, power balance constraints. The hourly production cost phase simulates hourly dispatch schedules of generators and energy storage systems and solves for the least-cost dispatch (in MWh).

13.5 Stacked Services Emulator

The Stacked Services Emulator (SSE) module uses an objective function to maximize potential hourly profits from energy storage services. The stacked-services emulator includes various applications of energy storage including but not limited to energy arbitrage, ancillary services, peak shaving, and renewable economic shifting. The study methodology is designed to be agnostic to energy storage technology assumption sets. Therefore, the SSE also includes all characteristics of energy storage, such as efficiency, size, duration, and the initial state of charge. The SSE returns the optimal hourly charge and discharge dispatch data and charts and calculates revenues and profits.

13.6 Simplified Levelized Cost of Energy

The simplified Levelized cost of energy (LCOE) is the average cost of the energy for a particular generator/storage unit over its economic life in terms of the present value. The methodology is adopted from US National Renewable Energy Laboratory (NREL) [10]. The parameters of the LCOE are the discount rate (i), the economic life (n), overnight capital cost, fixed O&M cost, and capacity factor while calculating the renewable units and energy storage systems. Detailed explanations and the units are provided in Table 35.

Table 35: LCOE Parameters & Units

Parameter	Definition	Unit
Discount Rate	Financial discount rate	%
Expected Capital Recovery Duration	Expected number of years to recover the capital (Economic life)	Years
Overnight Capital Cost	Investment cost of the generation/storage unit	$/kW
Fixed O&M Cost	Fixed operation and maintenance cost per kW per year	$/kW per Year
Capacity Factor	The expected capacity factor of the generation/storage unit	%

Capital Recovery Factor is calculated by using the discount rate and the economic life of the generator as shown in the following equation.

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

After that, the following formula is used to calculate the storage LCOE and solar LCOE.

$$LCOE = \frac{(Overnight\ Capital\ Cost * CRF + Fixed\ O\&M)}{8760 * Capacity\ Factor}$$

$$LCOE = \frac{(Overnight\ Capital\ Cost * CRF + Fixed\ O\&M)}{8760 * Capacity\ Factor} + (Fuel\ Cost * Heat\ Rate)$$

Another type of technology is the combination of the storage and solar system. In this case, the storage uses the solar system's generation; hence, the fuel cost is assumed zero. The charged energy would have been curtailed if not stored.

13.7 System Levelized Cost Of Energy

The system LCOE is calculated by considering total generation and all generators in the Barbados generation fleet. The formulation of the system LCOE is the sum of the generation cost, fixed O&M cost, and the annuities of generator/storage expansions divided by total energy demand. The formulation is provided as an equation below.

$$System\ LCOE = \frac{Total\ Generation\ Cost + Total\ Fixed\ O\&M\ Cost + Total\ Annuities\ of\ New\ Generators}{Annual\ Energy\ Demand}$$

14. Appendix-E: Study Objective and SOW

14.1 Study Objective

The main objective is to develop an Energy Storage Policy that meets the tenets of the BNEP and is in alignment with the new utility license and licensing regime. The following criteria highlight key areas for consideration and assist in conceptualizing the overall aim of the Policy.

1. A policy that provides for participation and empowerment of Barbadians within the energy sector. Indeed, it is envisaged that the ownership structure will reflect a high level of local investment.
2. A policy that takes into account storage systems deployed at the consumer level – that is at the residential, commercial, and or industrial premises of consumers- is referred to as "behind – the meter- storage".
3. A policy that will facilitate the Fair-Trading Commission (FTC) to then develop the appropriate tariffs for each of the identified services thus enabling the development of a market for energy storage services.

14.2 Scope of Work

The scope of this study is to create a framework and work plan for developing the Energy Storage Policy in Barbados. The scope includes the following items:

Identify the technical and economic benefits of storage services to the power system inclusive of the rationale for each service to advance the Barbados National Energy Policy, Delineate the services that can be provided by storage such as Energy arbitrage, transmission & distribution upgrade deferral, voltage and frequency regulation, voltage support, power reliability, demand charge management to name a few,

Provide policies and guidelines that speak to each energy service that storage can provide, while being flexible and responsive to emerging technologies and future market demands,

Propose guidelines to promote transparency and fair play in the market, including data sharing and the security of consumer data,

Determine the mechanisms that would need to be implemented in which consumers are remunerated for allowing the Systems Operator (utility) to withdraw electricity from the storage facility when needed,

Clearly define duties, roles, and responsibilities of key stakeholders in the Energy Storage Policy

In the execution of this study following items have to be considered:

Take into account the local context and other special considerations necessary for operation in a small island state with an isolated grid.

Ensure the policy does not exclude or negatively affect minority or under-represented groups,

Carry out stakeholder consultations as required to gather data and promote buy-in,

advise on the unintended regulatory and technical consequences and suggest initiatives that can be implemented to overcome them

Provide advice on the temporary measures that will be necessary to enable policymakers to make informed decisions as to the market transitions,

Consider how this new policy fits into existing policies and the laws of Barbados. In this regard, the consultant will be expected to provide a list of legislative amendments as required.

14.3 Risk Analysis

The forecasted storage economics and feasibility for the storage projects can be materially impacted as in the following list but not limited to:

- Valuation depends on participation in multiple sub-power markets and material differences can happen over time and can impact overall valuation.
- Any inaccuracies of warranties and representations of energy storage vendors in information for the project can impact project economics and feasibility.
- Any forward forecast statements are based on a set of assumptions where these forecasts can be materially affected by unforeseen micro and macroeconomic trends that impact project economics.
- The study relies on assumptions of cost estimates for storage, EPC, and other costs that can materially change project economics based on unforeseen changes.
- Market rules, regulation, policy, tax credits, and other as well as technical signals for grid services where changes can materially impact the project economics.
- Model is driven and data-driven conjecture will be relied upon

14.4 Terminology

#	Acronyms	Full Terminology
1	AA	Alternative Analysis
2	AEMO	Australia Energy Market Operator
3	AGC	Automatic Generation Control
4	BESS	Battery Energy Storage System
5	BLPC	Barbados Light and Power Company
6	BNEP	Barbados National Energy Policy
7	BNOCL	Barbados National Oil Company Limited
8	CHP	Combined Heat Power
9	CL	Cruise Liner
10	CPS	Clean Peak Standard
11	CSP	Concentrated Solar Power
12	DOE	US Department of Energy
13	DSO	Distribution System Operator
14	EIA	Energy Information Administration
15	EPRI	Electric Power Research Institute
16	ES	Energy Storage
17	ES	Energy Storage
18	FERC	Federal Energy Regulatory Commission
19	FiT	Feed-in Tariff
20	FOM	Fixed Operating and Maintenance Cost
21	FTC	Fair-Trading Commission
22	GDP	Gross domestic product
23	GHG	Greenhouse Gas Emissions
24	GoB	Government of Barbados
25	HFO	Heavy Fuel Oil
26	IRRP	Integrated resource and resilience plan
27	MCC	Marginal Cost of Cycling
28	MESBE	Ministry of Energy, Small Business, and Entrepreneurship
29	NCOE	New England States Committee on Electricity
30	NPC	National Petroleum Corporation
31	NTA	Non-Transmission Alternatives
32	PC	Production Cost
33	PV	Photo Voltaic
34	RPS	Renewable Portfolio Standard
35	SOC	State of charge
36	SRMC	Short-Run Marginal Cost
37	SSE	Stacked Services Emulator
38	T&D	Transmission and Distribution
39	TSO	Transmission System Operator
40	USD/tCO2	United States Dollars per tonne of Carbon Dioxide

#	Acronyms	Full Terminology
41	VAR	Volt-Ampere Reactive
42	VOM	Variable Operating and Maintenance Cost
43	VPP	Virtual Power Plant

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aceler

1 Broadway, 14th Floor
Cambridge, MA 02141

www.acelerex.com

Contact: info@acelerex.com

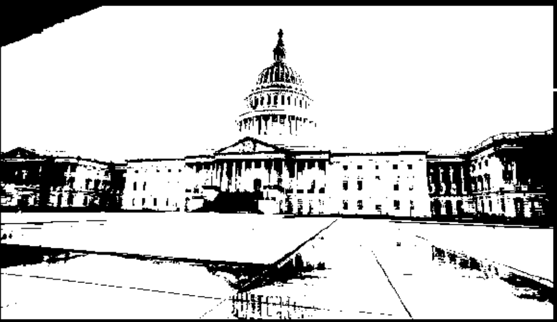
LinkedIn: https://www.linkedin.com/company/acelerex/

Acelerex is an independent consultant and software maker with offices in Cambridge, Miami, Washington D.C, Istanbul, Santiago, and Gujarat.

Acelerex Offices

Cambridge, MA

Santiago, Chile



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