Designing a Fully Renewable Electricity System for Bonaire

Integrating Flexibility to Balance Reliability, Affordability, sustainability and Energy Security

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Msc Complex System Engineering and Management

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by

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Preface

This thesis fulfills a goal I set for myself at a very young age while still living on my home island, Bonaire. I dreamed of reaching VWO, moving to the Netherlands to pursue a technical degree, completing a master's, and ultimately returning home to use my knowledge to support the island, the tropical paradise that has always supported me. At the time, it all seemed distant and difficult, but now it has become a reality.

Moving to the Netherlands was a significant step that brought new academic and personal challenges. Pursuing a master's degree was particularly intimidating, as I had always felt insecure about my English skills, a language I rarely used. Seeking guidance, I spoke with Ivo Bouwmans, the director of the COSEM master's program, whose encouragement gave me the confidence to begin the program with determination. Although the master's program brought more challenges than the bachelor's, I managed to stay on track and start my thesis as planned.

To complete my studies, it felt natural to return to Bonaire and conduct research that combined my academic knowledge with my personal connection to the island. Gerrit Scharenberg and Raynold Silberie, directors of WEB Bonaire (Water en Energiebedrijf Bonaire), offered me the opportunity to conduct my master's thesis at WEB Bonaire, for which I am deeply grateful. Being able to contribute to my island's sustainable future was highly motivating and meaningful to me. During my time at WEB, I gained valuable insight into the energy system behind the socket at my home. I observed the work of experienced and motivated professionals and saw how the company is taking significant steps toward innovation and energy transition. Cedric Daal played a key role in helping me access the right people and data, and I am sincerely grateful to him and everyone who supported me during my research.

This thesis period was also the first time in my academic journey that I experienced some delays. This was not due to struggle but because my interest in the topic led me to explore additional areas beyond the original scope. I became involved in extra learning opportunities at the company, such as observing the installation of a new transformer at the central distribution station and learning from the electrotechnical staff. I also waited for survey data on Bonairean perspectives regarding time-of-use tariffs, as I wanted my analysis to reflect local realities rather than imported assumptions.

I would also like to express my sincere gratitude to my supervisor, Petra Heijnen. I had a very positive experience with her during my bachelor's studies, and her dedication and attentiveness gave me full confidence that I would be well guided during this thesis. I am also grateful to Özge Ökur for her insightful feedback and constructive questions, which helped improve the quality of this thesis.

Looking back, I feel deep gratitude for the sacrifices and support that made this journey possible. Leaving my island and family, moving alone to the cold Netherlands, and facing moments of stress and growth have shaped me both academically and personally. I thank my parents for their unwavering support, my supervisors for their guidance, the staff at WEB Bonaire, my friends from Bonaire who shared this journey, and my master's friends who offered both academic and personal support. These have truly been blessings.

This thesis explores pathways for Bonaire's energy transition in response to climate change, focusing on strengthening the island's economy, reducing dependence on costly fossil fuels, and ensuring a reliable and climate-friendly electricity supply. My hope is that this work contributes to a more sustainable Bonaire, making the most of its abundant natural resources, where an engaged community and a shared vision guide the protection and growth of our island, allowing it to continue thriving as a paradise for generations to come.

Executive Summary

Bonaire, a small island in the Dutch Caribbean, faces profound challenges in its energy sector. Its geographical location makes it highly vulnerable to the effects of climate change, including sea level rise, coral reef degradation, and shifts in weather patterns. At the same time, the island's energy system depends almost entirely on imported diesel fuel. This reliance exposes households and businesses to volatile international oil prices and has led to some of the highest electricity costs within the Kingdom of the Netherlands. With a growing population and a steadily expanding tourism sector, energy demand on the island is expected to rise further, placing additional stress on the current system. In response, the government of Bonaire has set the ambitious target of achieving 100% renewable electricity.

This thesis examines how Bonaire can realistically achieve a sustainable energy transition. The work begins by analysing Bonaire's energy infrastructure and its institutional setting. The key actors in the system include the Water en Energiebedrijf Bonaire as the island's utility and water provider, ContourGlobal as the independent power producer, various government bodies and regulators, and the island's households and businesses as consumers. Their values and concerns were mapped into six criteria: economic viability, reliability, sustainability, energy security, energy access, and power quality. While all six are relevant, the analysis places greatest emphasis on the socio-economic criteria affordability (total system costs and production price), reliability, and sustainability (emissions and land use), with energy security considered as a long-term safeguard against external dependency.

The review of academic and technical literature highlights important knowledge gaps. Previous research on island energy transitions has focused mainly on wind and solar, with limited attention to other renewable options such as biofuel or ocean thermal energy conversion. The reviewed studies have tended to concentrate on technical indicators such as grid stability and cost, while giving less weight to long-term resilience, energy access, and the trade-offs between different evaluation criteria. Furthermore, flexibility measures are often reduced to the role of storage technologies, leaving out opportunities for demand response, flexible loads such as electric vehicles, and the integration of energy-intensive processes like seawater desalination. This thesis responds to these gaps by integrating a broader set of resources and flexibility options, and by explicitly assessing them against the set of stakeholder criteria.

The central research question guiding the study is: How can a fully renewable electricity system be designed for Bonaire that ensures reliability, affordability, sustainability and energy security? This overarching question is divided into four parts: (1) renewable energy sources technically feasible for the island, (2) demand-side flexibility based on load patterns and willingness to adapt, (3) the role of centralized and decentralized storage, and (4) the optimal mix of generation, flexibility, storage, and grid expansion to reach the island's 2030 target.

The first part of the analysis investigates the renewable energy potential of Bonaire. Wind and solar emerge as the foundations of the island's renewable future. The existing wind park at Morotín already performs above European averages, and expansion to 24 MW is planned. Solar photovoltaics provide the lowest-cost daytime electricity. However, because both wind and solar are variable, additional dispatchable resources are needed. Concentrated solar power with thermal storage can shift solar energy into the evening and night, providing reliability. Biodiesel offers a transitional option by allowing existing diesel generators to run on renewable fuel, while ocean thermal energy conversion presents a longer-term opportunity to generate constant baseload power and freshwater by using the island's steep offshore temperature gradients. Other technologies such as hydropower and geothermal are excluded due to the island's geography.

The second part of the analysis considers the potential for demand flexibility. A household survey conducted in 2025 found that 42% of households are willing to shift their electricity use voluntarily, while 26% would do so only in cases of supply shortages or grid limitations. Air conditioning is the dominant driver of evening peaks, but efficiency improvements and behavioural adjustments, such as raising thermostat set points, using fans alongside air conditioning, and pre-cooling in the early evening, can reduce loads. Refrigeration, lighting, and cooking also offer opportunities for efficiency, but limited shifting. Appliances such as washing machines, dryers, and dishwashers can easily be rescheduled to off-peak hours. Electric vehicles present a major challenge, since unmanaged charging in the evening could add more than 14 MW to peak demand by 2030. However, with managed charging and vehicle-to-grid, this demand can become a flexible resource, store midday solar surplus, and supply power in the evening.

A survey of 38 major businesses revealed high but incomplete adoption of efficiency measures. Many businesses already operate backup generators, and there is a growing uptake of rooftop solar generation. These developments need to be coordinated with demand-side management to ensure that flexibility is used in ways that effectively support system needs. The Water en Energiebedrijf Bonaire also operates the island's drinking-water plant, which accounts for about 7.5% of total electricity consumption. An interview with the plant manager confirmed that the facility cannot frequently switch its reverse-osmosis trains on and off without damaging the membranes. This makes the water plant a candidate for limited but still meaningful demand response.

The third part assessed storage both centrally and in decentralized configurations. The existing battery at ContourGlobal provides some balancing capacity, but expanding batteries alone to cover all variability would be prohibitively expensive. While storage remains an important complement to wind and solar, the results show that greater system value can be achieved by combining it with demand flexibility and dispatchable renewables such as concentrated solar power and ocean thermal energy conversion.

To answer these questions, the study applies a modelling approach based on a linear optimal power flow formulation using the open-source software PyPSA. The electricity network of Bonaire is represented with its main substations, distribution lines, existing generation units, and battery storage. The model combines inputs on hourly electricity demand, renewable resource availability, cost assumptions, and the physical limits of the grid. Demand growth is projected along two possible trajectories, one assuming a 3% annual increase and the other assuming 6%. The model runs at hourly resolution for September, which is the hottest and most electricity-intensive month of the year. Scenario analysis is then used to test different interventions, with each scenario evaluated against the stakeholder criteria of affordability, reliability, sustainability, and energy security. The first was a base case in which the island reaches 100% renewables by oversizing wind, solar, and batteries. The second introduced demand-side flexibility, shifting household cooling and electric vehicle charging to off-peak hours. The third distributed batteries across the grid to create decentralized storage. The fourth added flexible generation options such as biodiesel, concentrated solar power, and ocean thermal energy conversion.

The results show that the base case is technically able to meet demand but at very high cost and with strong dependence on weather conditions. Demand-side flexibility reduces total system costs while also improving reliability. Small-scale concentrated solar power provides a structural solution for evening peaks, while ocean thermal energy conversion offers the strongest long-term energy autonomy and the additional benefit of freshwater production. Biodiesel remains useful as a short-term backup but is not sustainable as a long-term option. Decentralized storage remains unused, as centralized storage is still cheaper due to economies of scale, and no constraints were found at the distribution grid level.

When evaluated against stakeholder criteria, the results suggest a clear strategy. Affordability is maximized by prioritizing demand flexibility. Reliability is strengthened by combining consumer participation with concentrated solar power, ocean thermal energy, and biofuel. Energy security is best achieved through ocean thermal energy conversion, which reduces dependence on imported fuels by drawing on local marine resources. Sustainability is ensured by limiting the use of biodiesel, reducing emissions through demand-side management and storage. Demand-side management lowers the need to oversize generation technologies, thereby reducing both capacity requirements and land-use impacts. There is still space for baseline wind and solar development without harming the environment. When land intensity is considered, OTEC is the most efficient option, as most of its infrastructure is offshore and only a minimal onshore footprint is required for turbines and heat exchangers.

This thesis makes a practical contribution to Bonaire by providing energy transition pathways that combine technical, economic, and social dimensions. It shows that consumer flexibility, concentrated solar power, and ocean thermal energy conversion can deliver reliability, affordability, and sustainability more effectively than simply oversizing wind, solar, and batteries. It also contributes to academic knowledge by extending the literature on small island developing states, demonstrating how behavioural measures and emerging technologies can reshape system design in practice.

A fully renewable electricity system for Bonaire by 2030 is feasible. To achieve it, the island must expand its wind and solar capacity, but this alone will not be sufficient. It must also engage households and businesses in flexible demand practices, adopt transitional reliability measures, and prepare for the introduction of new technologies such as concentrated solar power and ocean thermal energy conversion. Above all, it must strengthen its data collection and system planning, since reliable information is essential for managing demand, forecasting generation, and coordinating investment. If these steps are taken, Bonaire can achieve its target and become a regional leader in renewable energy, securing a system that is reliable, affordable, secure, and sustainable.

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Chapter 1: Introduction

This chapter introduces the central challenges that drive Bonaire's energy transition and frame the research problem. It begins by outlining the environmental motivation for the transition, followed by the socioeconomic and technical barriers that shape it. The chapter then presents the research goals, explains the chosen approach and scope, and situates the study within the MSc Complex Systems Engineering and Management (CoSEM) program. Finally, it provides an outline of the overall thesis structure.

1.1 Climate change challenges and energy transition motivation

As global urgency around climate change intensifies, Bonaire, a Dutch Caribbean Island, faces both profound risks and significant opportunities to reduce its carbon footprint. Climate change poses a set of interrelated threats to the island's environment, society and economy. Rising sea levels could submerge up to 20% of Bonaire, threatening infrastructure, communities and cultural heritage (Drayer, 2022). By 2050, permanent flooding is expected in parts of the low-lying nature reserves, including the saliñas, Lac Bay and Klein Bonaire, with risks expanding by 2150 to built-up areas such as Belnem and sections of Kralendijk if coral reef buffering is lost (Van Oosterhout et al., 2023). Coral reefs are also at severe risk from warming seas, bleaching and acidification, which would harm biodiversity, fisheries and tourism. Economically, the island could face up to USD 317 million in flood-related damage by 2050, together with tourism losses from reef decline that may deter over 100,000 visitors (Institute for Environmental Studies (IVM), VU University Amsterdam et al., 2022). Public health impacts, including heat stress and the spread of vector-borne diseases, further add to these risks.

At the same time, these threats underscore the opportunity for Bonaire to accelerate its transition to renewable energy by reducing emissions from diesel-based electricity generation. Leveraging favourable climatic conditions, the island has already integrated 29% of its electricity from wind and solar and aims to reach 60% by 2025 (Duurzame Energie – Water- en Energiebedrijf Bonaire, n.d.). This transition, supported by USD 33.6 million in Dutch government investment, is essential not only for environmental sustainability but also for securing affordable and reliable electricity that underpins economic growth (Samson, 2022). Although Bonaire's contribution to global greenhouse gas emissions is minimal and its transition will have little effect on the global climate crisis, the island's acute climate vulnerability makes the shift to renewable energy an urgent local priority. In this sense, climate risks provide the strongest motivation for Bonaire's transition while also aligning with the wider global ambition for clean energy. Beyond these environmental drivers, Bonaire faces significant socioeconomic and technical challenges that shape the path of its transition, challenges that are examined in the following subchapter.

1.2 Socioeconomic and technical challenges in Bonaire's energy system

As seen in the previous section, climate vulnerability provides the strongest motivation for Bonaire's energy transition. The urgency of the transition is also shaped by socioeconomic and technical challenges with direct societal relevance. These challenges mainly concern affordability and energy security on the one hand, and growing demand and system reliability on the other.

1.2.1 Affordability and energy security challenges

Socioeconomic challenges in Bonaire's energy system are most evident in the high cost of electricity, and therefore a cost-effective energy transition is vital for the island. The small scale and geographic isolation of the system results in comparatively high production prices, with residents spending up to 25% of their income on electricity (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022a). In comparison, the average wholesale electricity price in the European part of the Netherlands during 2024 ranged between USD 0.065 and 0.11 per kWh (Fraunhofer ISE, 2025; EnergyPrices.eu, 2025). This is over three to five times lower than Bonaire's production price, largely due to Bonaire's high dependency on imported diesel for generations, limited economies of scale, and lack of access to interconnected grids that can balance variability at lower cost.

In January 2024, the total production price on Bonaire was USD 0.3386 per kWh (Acm, 2023), composed of two main components. The first is the base production cost, set at USD 0.1410 per kWh, which covers non-fuel operating expenses such as labour, maintenance, depreciation, and financing. The second is the fuel cost, which accounts for USD 0.1976 per kWh. ACM calculates this based on the amount of diesel needed for generation and the prevailing diesel price (Acm, 2023). With diesel generation making up 69.47% of total electricity production, Bonaire is highly vulnerable to price volatility and import dependency. Fluctuations in global diesel markets are immediately reflected in household and business bills, while reliance on imported fuel undermines long-term energy security. Reducing this dependency through greater renewable integration is therefore not only an environmental necessity but also a socioeconomic imperative, essential for improving affordability, reliability, and energy security in Bonaire's power system (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022a).

1.2.2 Demand growth and reliability Challenges

The main technical challenges in Bonaire's energy system arise from steadily growing electricity demand and the difficulty of maintaining reliable supply. Electricity demand in Bonaire has grown steadily over the past decade, driven primarily by tourism growth, economic expansion, and population increases. Between 2014 and 2024, the number of electricity consumers rose from 9,373 to 13,403, an overall increase of more than 40% (WATER- EN ENERGIEBEDRIJF BONAIRE N.V., 2024). Annual growth rates have consistently ranged between 3% and 4%, as seen in appendix A. Small-scale consumers and prepaid electricity users account for the majority of new connections, reflecting population growth. Large-scale consumers, such as supermarkets, hotels, and apartment complexes, although smaller in number, represent a stable and significant share of total demand, largely linked to the tourism sector.

Figure 1 compares projected monthly electricity demand through 2030 with the estimated generation from a renewable portfolio comprising the existing 6 MW solar park at Karpata and the planned expansion of Bonaire's wind capacity from the current 11.1 MW to 24 MW by 2025 (Water- en Energiebedrijf Bonaire, internal report). The black dashed curves represent annual demand trajectories for 2021–2029, while the red dashed curve marks 2030, with the grey area indicating the 2020 baseline. The green (wind) and yellow (solar) bars show the expected monthly output from these fixed renewable capacities. By 2030, demand in all months is projected to exceed the output from renewables alone, with the gap most pronounced in the summer when peak demand reaches around 18 GWh. This highlights the necessity of investing in additional renewable capacity or other measures to ensure that supply and demand can be balanced efficiently as demand continues to rise.

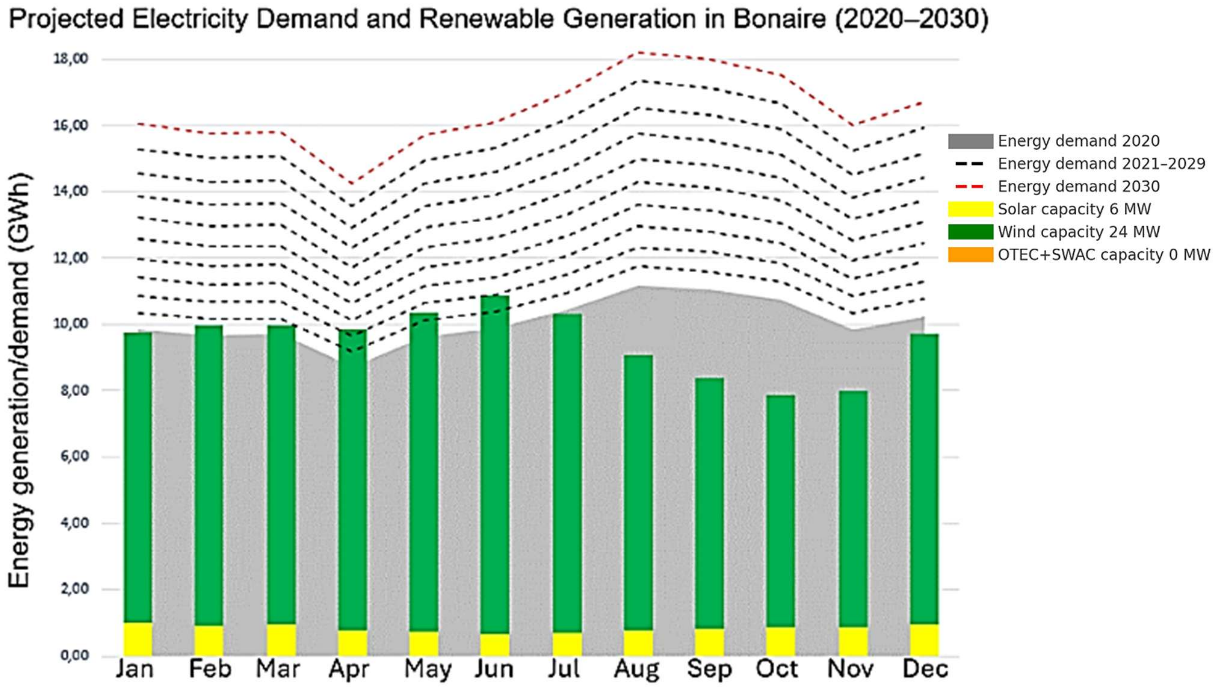


Figure 1: Projected monthly electricity demand (2021–2030) versus renewable generation from the planned 24 MW wind and existing 6 MW solar portfolio (GWh). This figure compares forecasted monthly demand with the expected output from the planned 24 MW wind capacity (up from the current 11.1 MW) and the existing 6 MW solar park (Water- en Energiebedrijf Bonaire, internal report).

On the technical side, achieving 100% renewable energy in Bonaire is feasible, but rising demand and the variability of solar and wind add complexity to maintaining system reliability. TNO's recent study indicates that increasing renewable penetration to 70–80% could reduce production costs; however, complete decarbonization will require substantial additional capacity to ensure stability throughout the year (Energy.nl, 2024). Balancing supply and demand in real time is particularly challenging in a small, isolated grid without regional interconnections, and at present diesel generators provide the main stabilizing capacity. Yet reliance on them is incompatible with long-term decarbonization goals. The importance of reliable supply is also evident in recent years: annual blackouts, most often on hot days when cooling demand peaks, have caused frustration among residents, while the August 2023 heatwave prompted Water- en Energiebedrijf Bonaire (WEB), the network operator, and ContourGlobal Bonaire (CGB), the sole power producer, to warn of possible disconnections if demand exceeded available capacity. As they explained, the hottest months coincide with hurricane season, and in the wake of several storms the island experienced paradoxically low wind speeds, sharply reducing wind power output just as demand for air conditioning reached record levels (WEB & CGB, 2023). These incidents underline that reliability is not only a technical requirement but also a core social priority, making it one of the central challenges for Bonaire's transition to a fully renewable system. Measures are needed to enable Bonaire to meet growing demand, improve reliability, and reduce dependence on imported diesel, aligning the island's energy system with both environmental and socioeconomic goals.

1.3 Bonaire’s energy transition: from challenges to research goals

Bonaire’s energy transition is both an environmental necessity and a socioeconomic imperative. The island’s high vulnerability to climate change, heavy reliance on imported diesel, and steadily rising electricity demand on a fast-growing island create strong drivers for rapid decarbonization. However, these same factors also present significant challenges, particularly in maintaining affordability, reliability, and energy security as the share of variable renewable energy increases.

The technical feasibility of achieving 100% renewable electricity is supported by studies such as TNO (Energy.nl, 2024). Yet reaching this goal in an isolated island grid will require substantial new capacity in solar, wind, and storage to ensure year-round reliability. To address the high investment costs associated with this expansion, additional interventions will be necessary to balance generation and demand in a cost-effective way. Whether technical or institutional in nature, these interventions must be evaluated not only for their technical performance but also considering Bonaire’s current socioeconomic challenges, including economic viability, contribution to energy security, and consistency with long-term decarbonization goals.

The effectiveness of renewable generation is inherently tied to local climatic and geographical conditions, including trade wind availability, solar irradiance, and marine resource potential. This means Bonaire’s transition strategy must be context-specific, ensuring that technological, economic, and social solutions are tailored to the island’s unique circumstances, resource profile, and public support.

This research addresses these challenges, namely high investment costs, dependence on imported diesel, rising demand, and the reliability risks of variable renewable generation, by assessing the most suitable renewable generation mix and evaluating complementary technical and/or institutional interventions for Bonaire. The aim is to design a pathway that balances decarbonization with key societal priorities such as affordability and reliability.

1.4 Research approach

Given that this research focuses on designing a fully renewable electricity system for Bonaire, a design-oriented approach seems the most appropriate. However, such a system is not a single artifact but a complex socio-technical network in which technical, institutional, and social components are highly interdependent. Bonaire’s energy system can be understood as such a network, where infrastructures and socioeconomic–institutional dimensions are tightly interwoven. On the technical side, renewable generation, grid capacity, and storage systems must operate in coordination, as imbalances in one element directly affect overall reliability. At the same time, these technical components are closely linked to institutional and social aspects such as consumer behaviour, energy prices, and policy frameworks. The two layers are mutually dependent: technical performance is shaped by institutional choices, while socioeconomic outcomes are conditioned by the reliability and affordability of the technical system. For this reason, the system must be analysed and designed as a whole rather than in isolation.

A modelling approach is well suited to this task because it enables the assessment and optimization of systems with multiple interdependent elements (SEN232A Master Thesis Research Design, n.d.). In Bonaire’s case, the model captures these interconnections to minimize system costs, meet demand throughout the year, reduce risks to energy security, and advance decarbonization objectives.

An inductive modelling logic is applied, meaning that findings emerge from systematic analysis of data rather than from predefined hypotheses (Thomas and School of Population Health, University of Auckland (2003)). In practice, empirical inputs, such as demand profiles, wind and solar availability, and technology costs, are iteratively used to optimize system configurations, while evaluation criteria are informed by stakeholder analysis and aligned with the research objectives. This inductive process directly links data, modelling, and research objectives in a transparent and defensible way, producing a system-level design rather than isolated technology assessments.

It is important to recognize that models are simplifications of reality and contain inherent uncertainties (Quay & Frangos, 2010). Resource availability and demand growth, for instance, are difficult to predict precisely. Nevertheless, modelling remains indispensable in contexts like Bonaire, where real-world experimentation is not feasible. To improve robustness, scenario-based analyses are applied to account for uncertainties such as demand growth and technology costs, quantify their impact, and strengthen confidence in the results and recommendations for system interventions.

1.5 Research scope

This research focuses on identifying the technologies, capacities, and measures required to meet Bonaire's growing electricity demand cost-effectively while supporting the island's decarbonization objectives. The study emphasizes reducing dependence on imported diesel and ensuring a reliable supply in an isolated system without increasing reliability risks.

The research focuses on planning for 2030, a near-term horizon where demand forecasts and spatial development plans are relatively reliable. The primary aim is not to produce a perfect prediction but to test different interventions under realistic stress conditions. The study does not focus on fine-scale electrical engineering aspects such as low-voltage distribution feeders to individual consumers, reactive power and voltage control, detailed protection schemes, or N-1 security analysis. While these elements are essential for operational studies and detailed engineering design, they add complexity without substantially improving insights for long-term investment decisions. Instead, the research takes a socio-economic perspective. The objective is to develop a reliable and affordable pathway to 100% renewable electricity that supports Bonaire's long-term decarbonization goals, with particular attention to identifying the most effective combination of technologies and institutional measures to reduce system costs in line with the island's technological, climatic, and social conditions.

1.6 Alignment to Complex System Engineering and Management

This thesis is closely aligned with the MSc Complex Systems Engineering and Management (CoSEM) program, and specifically the Energy track (Complex Systems Engineering and Management, n.d.). The central challenge of designing a 100% renewable electricity system for Bonaire exemplifies a socio-technical problem, where technical infrastructures, institutional arrangements, and social dynamics are deeply interdependent. Renewable generation, storage, and grid infrastructure must be understood in relation to regulation, investment planning, and market structures, as well as social factors such as public acceptance and consumer behaviour. This integrated perspective reflects CoSEM's design philosophy, which combines technological, governance, behavioural, and economic dimensions to develop effective and sustainable solutions.

By applying system modelling to optimize technical components and exploring institutional interventions aimed at reducing system costs, the thesis engages directly with the challenges highlighted in the Energy track. Its focus on renewable integration, grid planning, and cost-effective decarbonization aligns with the Energy track's goal of designing and managing future energy systems that are sustainable, reliable, and socially robust.

Finally, the interdisciplinary character of this research, combining engineering analysis with economic, policy, and social considerations, resonates with CoSEM's teaching approach, which blends systems engineering with management and process design. In this way, the thesis contributes not only to Bonaire's energy transition but also to CoSEM's mission of addressing global socio-technical challenges in the energy domain.

1.7 Thesis outline

This thesis progresses from contextual analysis and literature review toward modelling, results, and interpretation. Each chapter addresses a specific sub-question that contributes to the overall analysis, while the concluding chapters synthesize the findings and explore their broader implications.

Chapters 2 to 4 establish the foundation of the study. Chapter 2 introduces the background of Bonaire's energy system, describing the current infrastructure and the main stakeholders with their value criteria. It also discusses the central challenges of the island's energy transition, particularly the supply–demand balance and the resulting need for flexibility options. Chapter 3 presents the literature review, synthesizing academic and technical insights on renewable energy transitions in island contexts. From this review, knowledge gaps specific to Bonaire are identified, which lead to the formulation of the main research question and sub-questions. Chapter 4 outlines the methodology, explaining how each sub-question is addressed by linking it to specific methods, data requirements, and modelling techniques. The chapter also introduces the conceptualization of Bonaire's electricity system as a linear optimization problem.

Chapters 5 to 8 provide the core analysis that feeds into the modelling framework. Chapter 5 examines Bonaire's renewable energy potential, analysing the technical feasibility of wind, solar, and other resources under the island's climatic and geographical conditions. These findings form the basis for system generation design. Chapter 6 focuses on demand flexibility, identifying different types of consumers, examining their load profiles, and evaluating both their willingness and potential to shift demand. Chapter 7 continues with storage flexibility, assessing the contribution of storage technologies to system reliability and cost reduction, with particular attention to their role in complementing renewable generation and reducing reliance on diesel. Building on these analyses, Chapter 8 implements the findings on renewable potential, demand flexibility, and storage in PyPSA, and outlines the intervention scenarios for the 2030 horizon.

Chapters 9 to 11 present, interpret, and conclude the study. Chapter 9 presents the model results, describing the system configurations of the different intervention scenarios. Chapter 10 discusses these results in relation to stakeholder criteria, explores broader implications for policy and planning, and reflects on the limitations of both the model and the research approach. Finally, Chapter 11 concludes the thesis by summarizing the answers to the research question and sub-questions, providing recommendations for policymakers and utilities, and identifying directions for future research.

Chapter 2: Background

This chapter establishes the foundation for analysing Bonaire's energy transition by examining the current state of the electricity system and the key values that guide its development. It begins with a description of the island's energy infrastructure, including generation assets, network configuration and institutional responsibilities. Building on this technical overview, the chapter then addresses the central challenge of balancing supply and demand in a system increasingly reliant on variable renewable energy. Different types of flexibility are introduced to frame the options available for ensuring reliability and affordability in a fully renewable context. Finally, the chapter maps the key stakeholders involved in Bonaire's energy transition and distils their shared value criteria, which provides the evaluative framework for subsequent system modelling and scenario assessment.

2.1 Current energy infrastructure

Bonaire's electricity system operates as an island microgrid, functioning entirely independently from mainland grids. These island energy systems are designed to operate independently, relying on fuel importation (Nurse et al., 2014) (Weir, 2018). The system is managed primarily by three entities. Water- en Energiebedrijf Bonaire (WEB) serves as the sole utility, overseeing electricity distribution, water services, and network management, including the operation of substations and the island's SCADA control system. ContourGlobal Bonaire (CGB) acts as the independent power producer, operating the island's hybrid diesel, wind, solar, and battery storage facilities under a long-term Power Purchase Agreement (PPA) with WEB (Lamboo et al., 2022). Curoil supplies the diesel fuel used for power generation and manages the island's fuel infrastructure, including the BOPEC storage site (Antilliaans Dagbald, 2020).

The spatial layout of Bonaire's generation and transmission system is shown in Figure 2 (geographical map adapted from Verweij, P.J.F.M et al. (2022), using WEB Bonaire internal technical data), which depicts the locations of major generation facilities, substations, and the 30 kV and 12.2 kV distribution networks (Sun et al., 2016). All primary generation facilities are concentrated at ContourGlobal's main production site, which integrates 34.96 MW of diesel generators, a 6 MW solar park, a 14 MW / 9 MWh Battery Energy Storage System (BESS) for short-term balancing and frequency regulation, and the grid connection for Bonaire's wind capacity (Menafn & Menafn, 2019). The 10.8 MW Morotin wind farm in the northeast consists of twelve Enercon E-44 turbines rated at 900 kW each, while a separate 330 kW Enercon E-33 turbine is located at Sorobon in the south near Lac Bai. Electricity from the Morotin wind farm is transmitted via 30 kV lines to the main production site, where it is combined with output from the diesel generators, the solar park, and the BESS. From there, power is dispatched through the high-voltage network either directly to the northern town of Rincon, which operates independently from the main urban grid or to WEB's Nobo substation in Kralendijk, where the SCADA control room manages operations, transforms voltage, and distributes electricity across the island's main urban areas. The Morotin site is scheduled for expansion to 24 MW by 2025, a key step in WEB and ContourGlobal's joint objective of increasing the share of renewables to 60% of annual generation (*Duurzame Energie – Water- En Energiebedrijf Bonaire*, n.d.).

Electricity production in 2024 is supplied by a mix of diesel, wind, and solar resources, as seen in figure 3. Diesel generation remains the dominant source, producing approximately 102.7 million kWh per year, followed by wind at 36.2 million kWh and solar at 8.9 million kWh (WEB, internal data, 2024). The monthly distribution of generation sources showing the continued importance of diesel, particularly during months with lower wind speeds or reduced solar output. Although renewable energy already accounts for around 30% of annual demand, WEB and ContourGlobal aim to raise the share of renewables to 60% by 2025.

Figure 2: Geographic Layout of Bonaire's Electricity Generation and Transmission Network (geographical map adapted from Verweij, P.J.F.M et al. (2022), using WEB Bonaire internal technical data. Map showing the spatial distribution of Bonaire's primary generation assets, substations, and transmission infrastructure. Key facilities include the ContourGlobal main production site with 28.5 MW of diesel generators, a 6 MW solar PV park, and a 14 MW/9 MWh Battery Energy Storage System (BESS), as well as the 10.8 MW Morotin wind farm and the 330 kW Sorobon wind turbine. The 30 kV and 12.2 kV transmission lines illustrate the power flows from generation sites to Rincon and Kralendijk's substation.

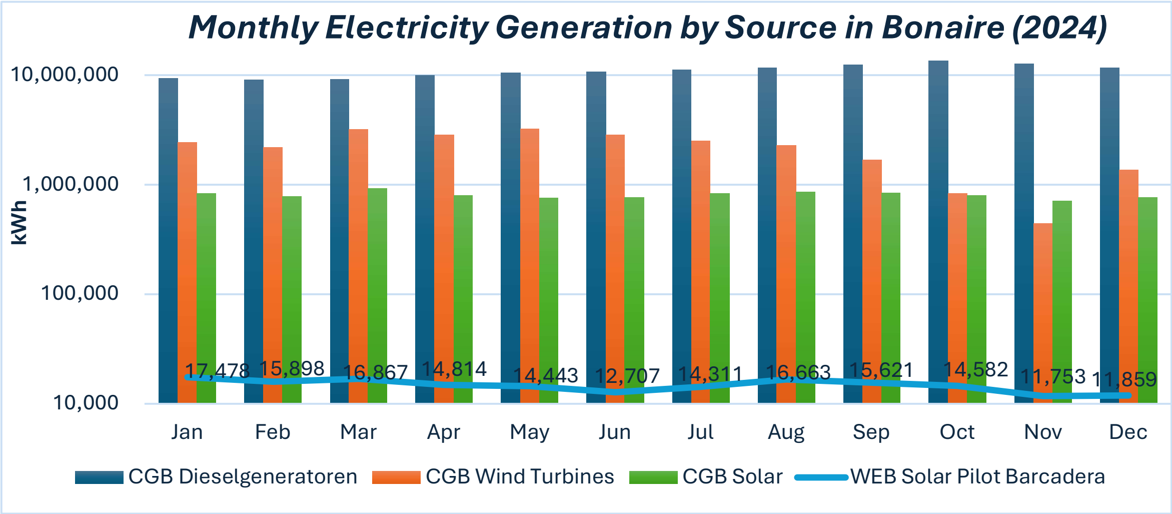


Figure 3: Monthly Electricity Generation by Source in Bonaire (2024) (WEB, internal data, 2024). Bar chart depicting monthly generation output by source, including ContourGlobal's diesel generators, wind turbines, and solar PV installations, as well as WEB's Solar Pilot project at Barcadera. The chart highlights diesel's dominant role in electricity supply, with wind and solar contributing significant but variable shares.

Bonaire benefits from its geographic location just north of the equator, which provides two strong and complementary renewable resources (Duurzame Energie – Water- En Energiebedrijf Bonaire, n.d.). The island experiences consistent trade winds for much of the year, driven by the atmospheric circulation patterns between the tropics. These winds are particularly steady from December to August, offering a predictable source of wind energy that supports continuous electricity generation. At the same time, Bonaire enjoys high solar irradiance levels due to its proximity to the equator, receiving strong and relatively uniform sunlight throughout the year. This makes solar photovoltaic generation highly productive, with minimal seasonal variation compared to more temperate regions.

However, the variability of both wind and solar resources still presents operational challenges. During the Atlantic hurricane season (June–November), local weather conditions can shift abruptly (WEB & CGB, 2023b). In the wake of regional hurricanes, wind speeds on Bonaire can drop significantly for days or even weeks, reducing wind turbine output. Cloud cover associated with tropical systems can further diminish solar production, even in this otherwise sun-rich location. These effects often coincide with periods of extreme heat, when air-conditioning use drives electricity demand to record highs. Under such conditions, the 9 MWh Battery Energy Storage System (BESS) becomes critical, absorbing short-term fluctuations, providing rapid frequency regulation, and supporting diesel generators during renewable output drops. Without any interconnection to mainland grids, all balancing, backup, and recovery operations must be handled locally, making system stability and resilience entirely dependent on the island's own generation assets and operational strategies.

The challenge of meeting peak demand without diesel generation is illustrated in Figure 4 (WEB, internal data, 2024), which shows that the highest recorded peak in September 2024 reached 26.26 MW. Under the current configuration, such peaks can be fully met by diesel alone in the absence of wind or solar. However, in a future 100% renewable system, these peaks would need to be covered entirely by variable renewable generation or other non-fossil backup solutions, such as large-scale storage or dispatchable renewable technologies. This requirement becomes even more significant when viewed alongside the expected year-on-year increase in total energy production shown in Figure 1 and appendix A.

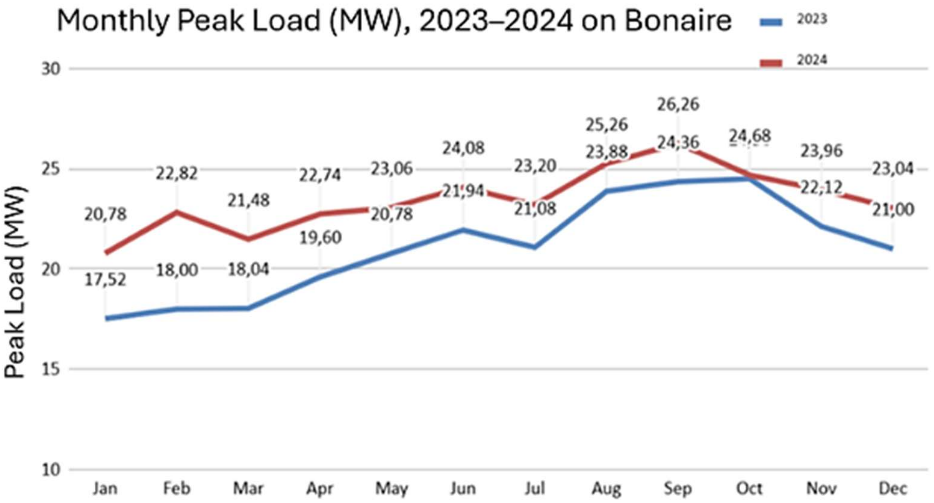


Figure 4: Monthly Peak Load in Bonaire (2023–2024) (WEB, internal data, 2024).
Line graph comparing monthly peak electricity demand between 2023 and 2024. The data shows a clear upward trend, with a record peak of 26.26 MW occurring in September 2024. This peak is currently within the capacity of diesel generation but would pose a challenge to meet solely with renewable sources under future decarbonization scenarios.

2.2 Balancing supply and demand: The flexibility challenge

As Bonaire moves toward its goal of a fully renewable electricity system, one of the most pressing challenges will be maintaining a stable balance between supply and demand in real time. Variable renewable energy (VRE) sources, such as wind and solar, are inherently intermittent, output fluctuates with weather and time of day and do not always align with demand. At present, diesel generators provide the primary means of stabilizing the grid, offering dispatchable capacity that can meet peak loads, such as the 26.26 MW recorded in September 2024, when renewable output is low. In a diesel-free system, such peaks would need to be covered entirely through renewable generation supported by flexibility measures. Without these measures, shortfalls would result in outages or forced demand curtailment.

Achieving 100% renewable energy for Bonaire requires flexibility options to balance supply and demand (Bundesministerium für Wirtschaft und Klimaschutz [Energiewende], 2019). Both technical and socio-technical approaches are needed for a stable, disruption-free energy supply. Flexibility, in this context, refers to the energy system's ability to reliably match supply and demand despite variability and uncertainty. According to Bekhrad et al. (2019), a robust energy system must be evaluated against four interrelated criteria: stability, reliability, affordability, and sustainability. Flexibility is the key enabler for meeting all four: it underpins stability by smoothing fluctuations and preventing frequency deviations, ensures reliability by providing backup during periods of low renewable output, supports affordability by reducing dependence on costly diesel imports or the need for excessive reserve generation capacity, and enhances sustainability by enabling higher shares of clean energy without compromising security of supply. Drawing on the conceptual framework applied by the IEA (International Energy Agency, 2021) and the Energy Transitions Commission (ETC, 2025), four major categories of flexibility options are especially relevant for Bonaire's energy transition: supply-side, demand-side, storage and grid expansion. Each of these strategies addresses different aspects of the variability challenge, and together they form the foundation of a secure, affordable, and sustainable 100% renewable energy system for Bonaire.

Energy storage refers to technologies that capture surplus renewable electricity for use during periods of low generation or high demand, playing a central role in buffering the mismatch between intermittent generation and consumption. These solutions would not only reduce reliance on diesel backup and defer costly grid reinforcements but also enhance operational flexibility by smoothing variability in wind and solar output. The location of storage assets is also significant. Centralized systems can function as system-wide reserves, optimizing dispatch across the grid. Decentralized storage is closer to consumers or renewable generation sites and can provide local flexibility, minimize transmission losses, and reduce the need for extensive network upgrades.

Grid expansion and modernization involve strengthening the transmission and distribution network to accommodate higher shares of variable renewable energy while. Key measures include increasing line capacity, upgrading connections, adding redundancy, replacing aging infrastructure, and constructing or modernizing substations to manage larger and more dynamic electricity flows. Modernization entails integrating distributed energy resources such as rooftop solar and electric vehicle charging infrastructure, which require the capability to manage bi-directional power flows. Smart grid technologies, including sensors, advanced metering, and automated control systems, enable real-time monitoring, rapid fault detection, and efficient response to fluctuations. Although smart meters are not yet in place on Bonaire, installation plans are underway as part of a broader strategy to improve digitalization and operational flexibility.

Supply-side flexibility and demand-side flexibility will be introduced in the next sections to provide a clear overview of flexible generation and consumption measures, which will be further assessed throughout the thesis together with energy storage and grid expansion.

2.2.1 Supply-side flexibility

Supply-side flexibility refers to the ability of generation assets to adjust their output in response to system needs (International Energy Agency, 2021). This is particularly important when integrating high shares of VRE, such as wind and solar, which are inherently weather dependent and have fluctuations in output. In Bonaire's current system, the hybrid generation facility operated by ContourGlobal, combining wind turbines, diesel generators, and limited battery storage, already provides a degree of dispatchability (Sustainable Energy – Water- En Energiebedrijf Bonaire, n.d.). However, as the island moves toward its 100% renewable energy goal, reliance on fossil-fuel-based dispatchable capacity will need to be replaced by renewable or low-carbon alternatives, while maintaining the same level of operational flexibility.

Table 1 presents a classification of renewable energy technologies based on their energy type and dispatchability potential (Tran & Smith, 2017). Dispatchable technologies are those that can be controlled to generate electricity when needed, providing flexibility to the system operator. Examples include hydropower, pumped hydro storage, geothermal plants, biofuel generation, ocean thermal energy conversion (OTEC), and systems based on salinity gradients. These technologies are particularly valuable in systems with high shares of variable renewable energy, as they can smooth fluctuations, provide reserves, and maintain system stability.

In contrast, non-dispatchable technologies, such as wind, solar PV, wave, tidal, and run-of-river hydro, generate electricity only when the resource is available, making it more difficult to align with demand. As shown in the table, Bonaire's current renewable portfolio, comprising solar PV and wind, is entirely non-dispatchable. While these resources are abundant and low-cost once installed, their variability means that without storage or backup generation, they cannot always guarantee supply (Tran & Smith, 2017).

In a future 100% renewable system, incorporating dispatchable renewable technologies could significantly improve reliability and stability.

Table 1: Renewable energy technologies classified by energy type and dispatchability, showing flexible (dispatchable) and inflexible (non-dispatchable) generation sources (Tran & Smith, 2017).

Renewable energy source	**Energy type**	**Dispatchability**
Hydropower	Gravitational Potential	Dispatchable
Micro-hydro	Gravitational Potential	Dispatchable
Run-of-river Hydro	Kinetic	Non-dispatchable
Pumped Hydro	Gravitational Potential	Dispatchable
Geothermal Power Plant	Heat	Dispatchable
Biofuel Power Generation	Chemical Potential	Dispatchable
Tidal Energy	Kinetic	Non-dispatchable
Wave Energy	Kinetic	Non-dispatchable
Current Energy	Kinetic	Non-dispatchable
Temperature Gradient	Heat	Dispatchable
Salinity Gradient	Osmotic	Dispatchable
Solar PV	Light	Non-dispatchable
Solar Thermal	Heat	Non-dispatchable
Onshore Wind	Kinetic	Non-dispatchable
Offshore Wind	Kinetic	Non-dispatchable

2.2.2 Demand-side flexibility

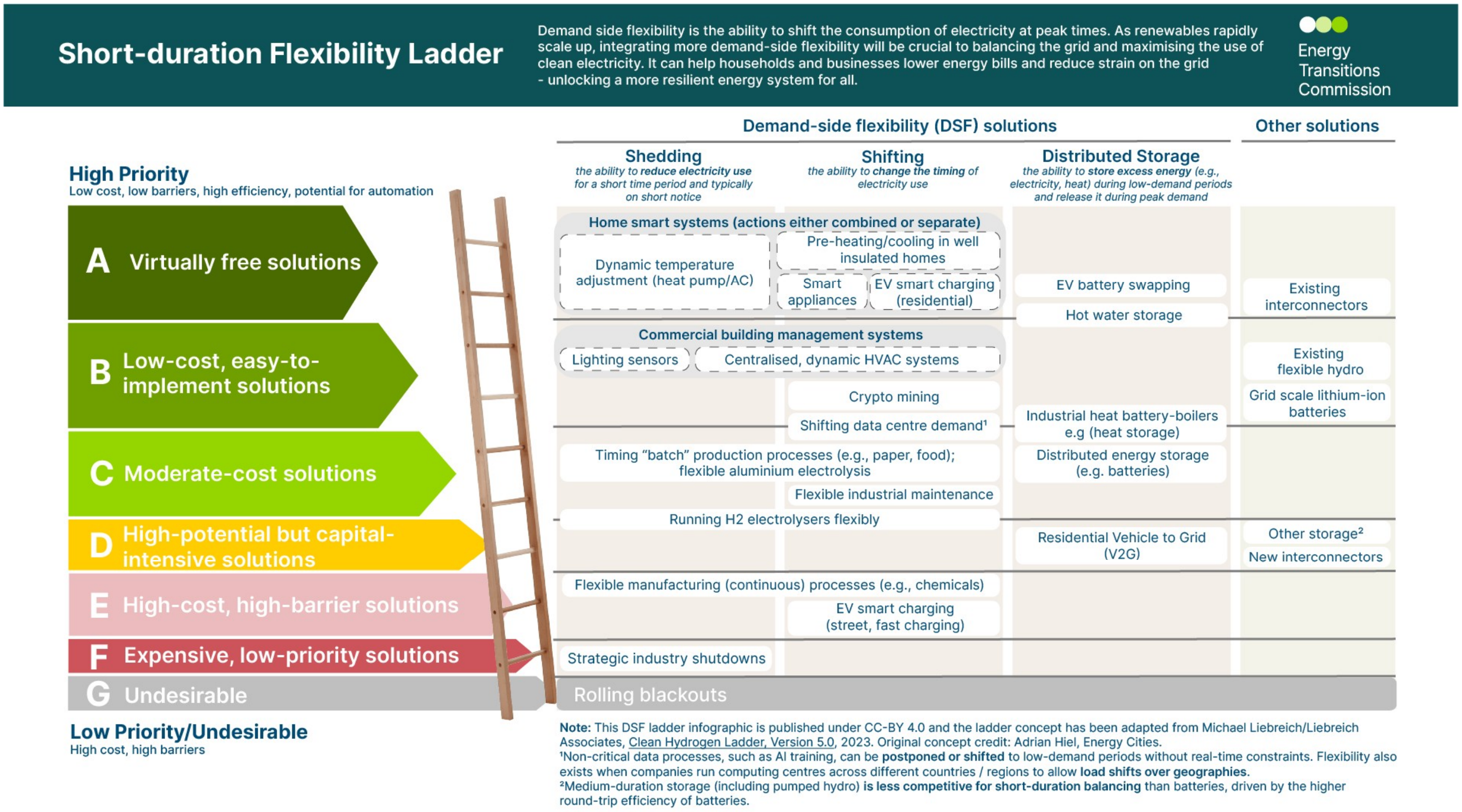
Demand-side flexibility (DSF) refers to the capability of the electricity system to adjust consumption so that demand better follows supply conditions, particularly those of variable renewable energy (VRE) such as solar and wind. By shifting loads to periods of high renewable output or low grid stress, DSF reduces the need for backup generation, prevents renewable curtailment, lowers system costs, and improves grid reliability. For consumers, DSF also enables cost savings by using electricity when prices are lower or when renewable availability is higher (Gridx, 2025).

DSF is realized through Demand-Side Management (DSM), a broad framework that encompasses both long-term structural measures and short-term operational responses (Albadi & El-Saadany, 2008). Structural DSM strategies include improving efficiency (e.g., LED lighting, efficient air conditioning, insulation), deploying smart meters and home automation for feedback and control, and integrating rooftop solar with household batteries to increase self-consumption and reduce peak loads. Within this framework, Demand Response (DR) represents the operational subset of DSM, focusing on short-term, often real-time adjustments to consumption in response to grid signals or price incentives (Stanelyte et al., 2022).

Typical DR measures include Time-of-Use (TOU) tariffs that encourage off-peak usage, smart EV charging aligned with solar production peaks, and deferrable loads such as desalination, refrigeration, or laundry services that can be shifted to periods of abundant renewable supply.

To guide the prioritization of measures, the Short-Duration Flexibility Ladder (ETC, 2025) ranks demand-side flexibility solutions by cost, ease of implementation, and potential for automation (Figure 5). At the top of the ladder are virtually free, high-priority measures such as automated temperature adjustments in well-insulated buildings, pre-heating or cooling, and smart appliance controls. These solutions can be rapidly deployed using existing technology. Low-cost, easy-to-implement measures include optimized EV charging and basic building energy management. Moderate-cost options involve more advanced systems such as dynamic HVAC controls in commercial facilities or scheduling flexible industrial processes.

High-potential but capital-intensive solutions, including Vehicle-to-Grid (V2G) and large-scale distributed storage, require significant investment but deliver valuable flexibility in high-renewable systems. Conversely, high-cost, low-priority actions, such as strategic industry shutdowns, are generally reserved for extreme grid stress scenarios. These strategies can be implemented in Bonaire, to effectively meet variable supply. Therefore, the feasibility and willingness of consumers on Bonaire will be assessed in this research.



Note: This DSF ladder infographic is published under CC-BY 4.0 and the ladder concept has been adapted from Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023. Original concept credit: Adrian Hiel, Energy Cities.

¹Non-critical data processes, such as AI training, can be **postponed or shifted** to low-demand periods without real-time constraints. Flexibility also exists when companies run computing centres across different countries / regions to allow **load shifts over geographies.**

²Medium-duration storage (including pumped hydro) **is less competitive for short-duration balancing** than batteries, driven by the higher round-trip efficiency of batteries.

Figure 5: Short-Duration Flexibility Ladder showing relative cost, priority, and ease of implementation for DSF measures (ETC, 2025)

2.3 Stakeholder analysis and value criteria

The transition to a fully renewable energy system in Bonaire is shaped by a diverse set of actors, each with specific interests, capacities, and responsibilities. The purpose of this actor analysis is to identify and prioritize the criteria that should be used to for assessing flexibility options and renewable energy system designs, ensuring that technical solutions align with the island's broader economic, environmental, and social objectives.

2.3.1 Government bodies & regulators

The government and regulatory actors are responsible for setting Bonaire's energy and climate strategy, enacting relevant policies, and overseeing the implementation of the transition. These institutions shape the legal, institutional, and financial frameworks that determine how the transition unfolds.

The Government of Bonaire (Openbaar Lichaam Bonaire – OLB) is the island's main legislative and executive body. It is accountable to residents and works in line with Dutch ministries. OLB manages spatial planning and development permits, which shapes future electricity demand and generation expansion (OLB, 2023). It also sets local priorities for energy and the environment, coordinates with national policy, and promotes the transition as part of its "Blue Destination" vision (European Comission, n.d.).

At the national level, the Ministry of Climate Policy and Green Growth provides direction and funding to align Bonaire with the Netherlands' carbon neutrality goals (Ministerie van Klimaat en Groene Groei, 2025). The Ministry of Economic Affairs supports the transition through subsidies, grants, and by helping to establish Bonaire Bon Transition (BBT). BBT is a state-owned body created to speed up renewable deployment and manage fuel logistics (BBT - Energie voor Bonaire, 2025). It acts as both a technical advisor and an infrastructure investor, working closely with OLB and WEB.

The Authority for Consumers and Markets (ACM) is the Dutch utilities regulator (Acm, 2023). It oversees electricity tariffs, protects consumers, and ensures fair markets. ACM also plays a central role in reviewing and approving new pricing schemes as Bonaire shifts to renewable energy.

Together, these actors determine whether Bonaire's energy transition is technically feasible, financially viable, and operationally stable. Their shared priorities reflect their specific roles within the energy system. System reliability is fundamental for the network operator (WEB) to maintain stable grid operations, for the producer (ContourGlobal) to ensure consistent generation, and for the fuel supplier (Curoil) to guarantee secure fuel delivery. Affordability requires coordinated action across all three: WEB manages tariffs and service equity, ContourGlobal controls generation costs, and Curoil influences fuel prices and logistics. Sustainability is embedded in their joint efforts to reduce fossil fuel dependence by integrating renewables, modernizing infrastructure, and supporting the transition to alternative fuels. Grid modernization depends on the network operator upgrading and expanding the system, while the producer and supplier adapt their operations to align with new technologies and resources. Finally, contract stability and operational efficiency underpin long-term planning and investment: stable agreements between these actors enable reliable service, efficient operations, and coordinated progress toward renewable goals. Together, these interconnected priorities shape the technical, financial, and operational foundations of Bonaire's energy transition.

2.3.2 Energy operators & producers

This group includes the entities that generate, manage, or deliver energy services, playing a pivotal role in the technical feasibility and daily functioning of the system. They manage infrastructure, ensure supply continuity, and execute plans that shape the pace and structure of the transition.

WEB Bonaire (Water- en Energiebedrijf Bonaire N.V.) is the state-owned utility responsible for electricity distribution, water services, wastewater management, and desalinated water production. Although it does not generate electricity, WEB is the sole buyer under a Power Purchase Agreement with ContourGlobal and manages the island's grid. It develops technical roadmaps, works closely with Bonaire Bon Transition (BBT) and the Government of Bonaire, and leads projects to integrate solar, wind, hybrid systems, and battery storage.

ContourGlobal Bonaire is the private power producer responsible for operating all of the island's current electricity generation assets. Under a long-term Power Purchase Agreement (PPA) with WEB, it runs the hybrid diesel–solar–battery plant at Karpata and manages the wind farms at Morotin (WATER- EN ENERGIEBEDRIJF BONAIRE N.V., 2024b). ContourGlobal holds significant operational influence, with a central role in renewable scaling efforts.

Curoil is Bonaire's sole fuel importer and is responsible for fuel logistics and storage (CUROIL | Who We Are, n.d.). In 2024, it was selected as the preferred bidder to take over the facilities of the Bonaire Petroleum Corporation (Bopec), consolidating its position in supplying fuels for electricity generation and transport (René, 2024). While its current activities focus on diesel, Curoil will also be responsible for enabling the introduction of alternative and sustainable fuels in the future.

Public actors such as WEB focus on equitable service delivery and alignment with societal objectives. Private actors like ContourGlobal and Curoil concentrate on operational performance and financial sustainability. Despite these differences, they share several key priorities that guide their actions. System reliability is essential to maintain a stable and secure energy supply. Affordability involves keeping energy accessible for consumers while ensuring that investments remain financially viable for utilities and producers. Sustainability reflects their shared commitment to reducing environmental impacts and supporting long-term transition goals. Grid modernization enables the integration of renewable resources and improves system performance. These priorities are supported by contract stability, which provides investment security, and by operational efficiency, which ensures that infrastructure and resources are used effectively. Together, these shared values form a common foundation for coordinated action among the network operator, the power producer, and the fuel supplier.

2.3.3 Energy consumers

Energy consumers form a broad and diverse group that includes households, businesses, public institutions, mobility actors, and technology providers. They shape demand, invest in renewable technologies, and influence public opinion and political priorities. Their behavior plays a decisive role in determining the pace and structure of Bonaire's energy transition. As potential providers of flexible demand, they are central targets for demand-side management measures that aim to match consumption with available supply.

Residential and housing stakeholders include households, individual consumers, and developers. With a steadily growing population, residential demand is rising, particularly for air conditioning, water heating, and mobility.

Public sector consumers, such as the airport, hospital, schools, government offices, and water and wastewater systems, depend on uninterrupted electricity for essential services. Their demand is largely inflexible, which makes reliability and predictable costs critical. Private sector consumers, including hotels, resorts, supermarkets, telecom providers, and industrial users, account for a significant share of demand. Their priorities focus on cost control and operational continuity, as energy costs directly affect competitiveness in Bonaire's tourism-driven economy.

Mobility and electric vehicle (EV) users are becoming increasingly important drivers of future demand. EV adoption is expected to grow rapidly, but on small and isolated grids unmanaged charging can create steep demand peaks and strain system reliability (Borlaug et al., 2021; Kandezi & Naeenian, 2021). Household charging alone can increase local electricity demand by up to 78% without smart coordination (Zhang et al., 2023). Consumers are also becoming producers, installing rooftop PV systems and, in some cases, battery storage. These prosumers reduce daytime demand on central generation and increase flexibility but also introduce new challenges in balancing the load curve (Xia et al., 2021; Cheng et al., 2023). This highlights the need for charging infrastructure, supportive policies, and effective demand-side management.

Together, these groups form both the foundation of current energy use and the main drivers of future demand. From their perspective, several priorities stand out clearly. They want electricity that remains affordable. They expect reliable service that supports their daily lives, operations, and essential services without frequent disruptions. They increasingly value sustainability, seeking cleaner energy options that protect the environment and align with long-term transition goals. They demand fair access to energy opportunities and transparent policy so they can trust and actively participate in the transition. While sustainability is gaining importance, stable prices and dependable supply remain at the core of their concerns.

2.3.4 Environmental & Nature protection organizations

Environmental stakeholders play a crucial role in ensuring that Bonaire's energy transition supports carbon neutrality while protecting its terrestrial and marine ecosystems. Their involvement focuses on integrating biodiversity protection and environmental considerations into spatial planning and policy. This establishes practical limits on where renewable energy infrastructure can be deployed, since unsuitable siting could harm sensitive habitats.

STINAPA, the National Parks Foundation of Bonaire, manages the island's protected terrestrial and marine ecosystems, including coral reefs, mangroves, and seagrass beds (STINAPA Bonaire, 2025). Through its advisory role, it directly influences where and how new energy infrastructure can be developed. The Dutch Caribbean Nature Alliance (DCNA), a regional conservation network, complements this role by linking Bonaire's ecological priorities to regional and global biodiversity agendas. It supports STINAPA through policy advocacy, scientific expertise, and funding channels, strengthening environmental oversight and ensuring that local planning aligns with wider conservation goals (DCNA, 2025).

Their shared priorities are grounded in modern Life Cycle Assessment (LCA) methods, which assess a wide range of environmental impacts beyond greenhouse gas emissions. International standards such as EN15804+A2 define fifteen core impact categories that cover air, water, land and soil, resource and material use, biodiversity and ecosystems, human health, and local disturbances such as noise or visual effects (Hillege, 2025). These methods help evaluate trade-offs, identify significant risks, and determine where renewable energy can be deployed with the least environmental impact. Environmental stakeholders use these assessments to guide the siting and approval of projects, ensuring that decisions reflect their shared values of biodiversity protection and ecosystem integrity.

2.3.5 Shared value criteria derived from stakeholder analysis

The stakeholder analysis reveals that, despite differences in roles and levels of influence, the main actors in Bonaire's energy transition share a common set of priorities. These criteria reflect both the technical requirements of a stable renewable energy system and the island's broader economic, environmental, and social goals. They form the analytical framework for evaluating energy system pathways and flexibility options.

Affordability and economic sustainability: Consumers focus on electricity costs, while government and regulators aim to maintain fair and stable tariffs. ACM sets prices based on total investment and operational costs, ensuring cost recovery for utilities. For operators, investment stability is essential to enable infrastructure upgrades. This criterion is reflected in total system costs and their impact on consumer tariffs.

System reliability and stability: All actors depend on a reliable power supply, especially service providers such as hotels that aim to deliver uninterrupted service to clients, and critical infrastructure such as hospitals, airports, communication systems, and transportation networks that must remain operational during disturbances. The system operator is responsible for maintaining stable grid operations under varying demand and increasing renewable generation. A reliable grid provides stable and continuous electricity, quickly restores service during interruptions, and withstands disruptions such as storms or equipment failures without prolonged outages (Energy Reliability and Resilience, n.d.). Reliability also involves maintaining voltage and frequency stability, ensuring sufficient generation capacity and network redundancy, and coordinating across the grid. Qualitative assessment can focus on generation and storage assets: evaluating the diversity and capacity of energy sources, and the availability of storage systems, to maintain supply during outages.

Environmental sustainability: The government conducts environmental impact assessments with input from STINAPA and the Dutch Caribbean Nature Alliance (DCNA) to ensure that Bonaire's energy transition supports environmental sustainability. Two key dimensions are central to this process: land use, which must account for the island's limited space and the need to avoid disrupting biodiversity and ecosystems; and greenhouse gas emissions and pollution, which align with global decarbonization goals while addressing local pollution that can harm human health and the natural environment. Other environmental impacts are also qualitatively evaluated where relevant to support informed and responsible decision-making.

Energy security and resilience: Energy security is not just about having uninterrupted access to energy, but also about securing energy supplies at an affordable price (IEA, 2022). This definition highlights two key dimensions: availability, which refers to ensuring continuous access to energy, and affordability, which focuses on maintaining prices that do not threaten economic stability. During energy transitions, when clean and fossil energy systems coexist, both traditional threats such as supply disruptions and new vulnerabilities such as critical mineral supply chain risks must be managed. Governments, system operators, and suppliers share the responsibility of reducing reliance on imported fuels and limiting exposure to external shocks. Energy security is evaluated qualitatively by examining the share of local renewable generation, use of imported fossil fuels, system flexibility, diversity of supply chains, and resilience of energy infrastructure.

Energy equity focuses on providing affordable, safe, and reliable energy while fairly sharing the benefits and risks of new technologies (Shamsi & Rahmati, n.d.). It is relevant for households, communities, system operators, and policymakers, ensuring that all groups benefit equally from the energy transition. Assessment considers the system's capacity to meet future demand, expand the grid, support self-generation, and ensure that new technologies do not create pollution or disrupt access for any community on the island.

Within this thesis, the focus is on the socio-economic dimensions of the energy system rather than on technical measures such as power quality, voltage, efficiency and frequency. Affordability is assessed through total system costs and their impact on consumer tariffs. Reliability and energy access are evaluated together to examine the system's ability to meet growing demand and maintain stable supply under different configurations. Environmental sustainability is assessed locally through land use considerations to protect ecosystems and globally through reductions in greenhouse gas emissions. Energy security focuses on long-term resilience and reduced dependence on imported fuels. New vulnerabilities, such as critical mineral supply chains for renewable technologies and storage, are assumed to be manageable since they involve one-time or limited supply needs rather than continuous imports like diesel for power generation. Technical performance metrics are excluded from the scope, while energy equity and access are incorporated into the reliability criterion, and the potential pollution or harm from new technologies is addressed within the environmental sustainability criterion.

Chapter 3: Literature Review

Before undertaking this thesis, a literature review was conducted to establish a solid foundation for understanding Bonaire's renewable energy transition and to identify critical research gaps. The review aimed to achieve three main objectives: (1) consolidate existing academic and technical knowledge on renewable energy systems in island contexts, (2) identify gaps that are specifically relevant to Bonaire's technological, climatic, and socioeconomic conditions, and (3) refine the main research question guiding this study.

3.1 Core concepts

The literature review search strategy is guided by a conceptual framework consisting of five core analytical elements: renewable energy types, classifications of electrical energy systems, geographical scope, system evaluation criteria, and flexibility options. Renewable energy plays a central role in achieving Bonaire's energy transition goals by reducing dependence on fossil fuels and diesel generators. Therefore, the review will explore the range of renewable energy technologies applicable to Bonaire, with particular attention to options beyond conventional PV and wind systems. Analysing energy systems with technical specifications similar to Bonaire's provides valuable insights into its unique challenges and opportunities. Given its geographic isolation, Bonaire's energy system is classified as an islanded system, exhibiting the characteristics of decentralized, off-grid microgrids that rely heavily on imported fuels (Nurse et al., 2014; Weir, 2018). Defining the geographical scope is essential, as climatic factors such as wind availability and solar irradiance directly affect the potential and effectiveness of renewable energy sources, and comparable regions can offer relevant lessons. The review will also identify research on renewable energy transitions that assess the shift from the perspective of local stakeholders, using criteria aligned with Bonaire's priorities: affordability, sustainability, energy security, and reliability. Finally, achieving 100% renewable energy for Bonaire requires the integration of flexibility options to balance supply and demand. Exploring these elements provides a solid basis for understanding Bonaire's energy transition, considering both technical feasibility and socio-economic.

Figure 6 illustrates how the five core categories of the review interconnect in supporting Bonaire's ambition of 100% renewable electricity. The geographical scope defines the contextual conditions that enable renewable energy adoption, while renewable energy itself forms the core of the transition. Electrical systems provide the structural basis for integration, and system criteria offer a way to measure performance in terms of reliability, affordability, and sustainability. Finally, flexibility options, such as storage and demand management, ensure stability and balance. Together, these elements highlight the multidimensional approach required for a successful energy transition on Bonaire.

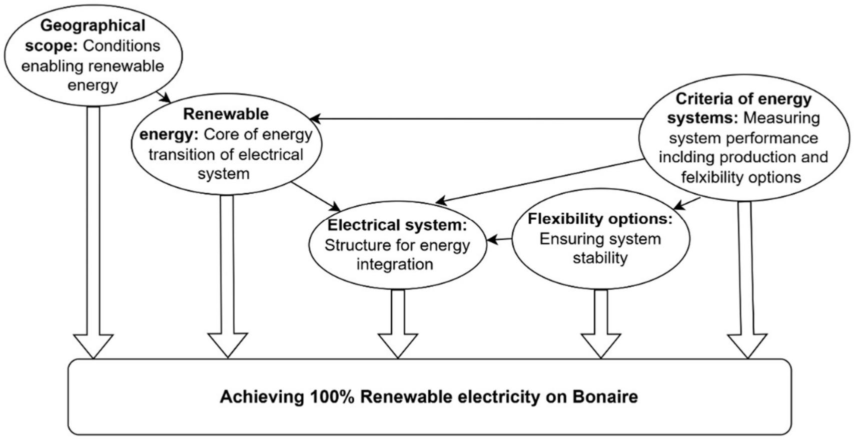


Figure 6: Conceptual map of key factors guiding the literature review, supporting the assessment of pathways toward 100% renewable electricity on Bonaire (own elaboration)

3.2 Methodology: Literature review process

This review applied the PRISMA method, beginning with the identification of relevant studies. Scopus was chosen as the sole database because of its comprehensive coverage of peer-reviewed academic literature. The search strategy was structured around five key concepts: renewable energy sources, geographical scope, type of electrical system, energy system criteria, and flexibility options. The full list of keywords is presented in Appendix B1, and the complete search strategy and selection process are outlined in Appendix B2. The initial search, which required studies to address renewable energy integration in island systems together with either system criteria or flexibility options, produced 4,163 results.

From this pool, the screening process progressively refined the dataset. The first refinement retained articles that considered energy system criteria, while a further filter focused on studies that also addressed flexibility measures such as storage and demand response. To narrow the scope specifically to the Caribbean context, an additional search was conducted without the keyword *island*, which yielded further relevant studies related to the Caribbean region.

The remaining articles were then assessed in full to determine their eligibility. Studies were excluded if they did not specifically address Bonaire or comparable island-based energy systems. Also excluded were works dealing only with temporary post-disaster supply, climate resilience without direct energy system analysis, education-focused research, or non-island applications such as ship energy systems.

The final set comprised 13 studies. These directly examine renewable energy integration in Bonaire or similar Caribbean Island, explicitly considering both system criteria (e.g., reliability, affordability, resilience) and flexibility measures (e.g., storage, demand management, balancing). Collectively, these studies form the evidence base for the present review.

3.3 Synthesis

An overview of the articles included in the critical review is presented in Table 2. As highlighted in the overview, wind and solar are the most discussed renewable sources, while hydrokinetic energy is mainly seen as a backup. This aligns with Bonaire’s current energy mix, where wind and solar dominate. Backup options like biodiesel, biomass, and Ocean Thermal Energy Conversion (OTEC) are underexplored in the literature.

The articles mainly focus on the Caribbean, including Bonaire, emphasizing grid stability, reliability, and affordability. However, they offer limited exploration of renewable sources beyond wind and solar. Flexibility options like demand-response, electric vehicles, and sustainable backups are rarely analysed.
The literature primarily examines islanded decentralized grids relevant to Bonaire. While grid stability, reliability, and affordability are discussed, none comprehensively analyse all criteria together. Storage and hybrid backup systems are common solutions, but there is little focus on Bonaire-specific scenarios, particularly demand-response mechanisms.
One article discusses desalination as a deferrable load with energy storage, which is relevant for Bonaire's energy-intensive water system. This presents an opportunity for future research to explore such flexibility options to address both energy and water challenges.

Table 2: overview of selected literature

Authors (Year)	Renewable Energy	Geographical scope	Type of Energy System	Criteria of Energy System	Flexibility Options
Polselli, P., Singh, P. (2024)	Wind, solar	Saint Lucia, Caribbean	Distributed Grids	Reliability	Energy Storage
Hoody, P., Chiasson, A., Brecha, R.J. (2023)	Solar Energy, Wind Energy, Concentrating Solar Power	Antigua and Barbuda, Caribbean	Decentralized Grids	Cost-effective	Energy Storage (Battery and Hydrogen Storage)
Sadeek, S., Chakrabarti, D., Papathanasiou, M.M., Ward, K. (2023)	Sustainable Energy (General Renewable Energy)	Trinidad and Tobago, Caribbean	Decentralized Grids	Cost-effective, Greenhouse Gas Emissions Reduction	-
Sterl, S., Donk, P., Willems, P., Thiery, W. (2020)	Wind Energy, Hydrokinetic Energy	Suriname, Caribbean, South- America	Islanded Mode/Grid Integration	Grid Stability, Decarbonization	Flexible Hydropower Operations
Baldizon, R.C. (2020)	Solar Energy	Caribbean, America	Distributed Generation	Resiliency, Reliability, Independence, Security	-
Budes, F.A.B., Ochoa, G.V., Obregon, L.G., Arango-Manrique, A., Álvarez, J.R.N. (2020)	Solar Energy, Wind Energy	Colombia, Caribbean region	On-grid System	Environmental Impact, Cost-effectiveness, Energy Efficiency	Hybrid Optimization
Tariq, J. (2020)	Solar Energy, Wind Energy	Bonaire	Island Energy System	Reliability, Affordability	Energy Storage (Hydrogen, Lithium-Ion Batteries)
Valencia, G., Benavides, A., Cárdenas, Y. (2019)	Solar Energy, Wind Energy	Colombian Caribbean Region	Hybrid Energy System	Cost-effectiveness, Reduction of CO2 Emissions, Energy Efficiency	Fuel Cell (Hydrogen and Oxygen Flow Control), Hybrid Multi objective Optimization
Taibi, E., Fernández del Valle, C., Howells, M. (2018)	Solar Energy, Wind Energy	Barbados, Caribbean	Decentralized Grids	Cost-effective, Grid Stability	Electric Vehicles (Smart Charging, Vehicle-to-Grid)
Vazquez, L., Majanne, Y., Castro, M., (...), Vilaragut, M., Diaz, D. (2018)	Sustainable Energy (General Renewable Energy)	Cuba, Caribbean	Distributed Generation	Security, Efficiency, Renewable Integration	
Watson, D., Binnie, Y., Duncan, K., Dorville, J.-F. (2017)	Solar Energy, Wind Energy	Caribbean (focus on Jamaica)	Hybrid Renewable Energy Systems (HRES)	Reliability, Efficiency	Hybrid Optimization
Miranda, D.S., Sun, Y., Cobben, J.F.G., Gibescu, M. (2016)	Solar Energy, Wind Energy	Bonaire	Island grid	Grid Stability, Frequency Stability	Battery Energy Storage, Electric Vehicles
Bognar, K., Blechinger, P., Behrendt, F. (2012)	Solar Energy, Wind Energy	Petite Martinique, Grenada , Caribbean	Microgrid	Cost-effectiveness, Resource Efficiency	Desalination as Deferrable Load, Energy Storage

3.4 Knowledge gap and research question

The literature review reveals several important gaps in relation to Bonaire's energy transition. Variable wind and solar energy dominate the discussion, while other dispatchable renewable sources such as biodiesel, biomass and ocean thermal energy conversion (OTEC) are rarely studied. This limits the possibilities for a more diverse and resilient energy mix. The reviewed studies focus strongly on technical aspects such as electricity quality, grid stability and efficiency. However, they give far less attention to long-term concerns such as energy security, reliability, land use limitations on a small island and energy access, both of which are critical as demand continues to grow. None of the studies provide a full assessment of the criteria that stakeholders in Bonaire consider most important. These criteria are affordability (or economic viability), reliability, sustainability and energy security. No study evaluates all of them together or explores the trade-offs between them, even though this would be necessary to reflect stakeholder priorities in practice.

Flexibility is another area where gaps appear. Storage is the most frequently discussed solution, but other important measures receive only limited attention. These include demand-response mechanisms, sustainable backup systems and the use of flexible loads such as electric vehicles, which could play a valuable role in Bonaire's energy system. The potential integration of desalination systems as deferrable loads is also overlooked, even though water production is one of the island's most energy-intensive processes.

Overall, the literature does not provide a thorough analysis that integrates different renewable energy sources, a broad range of flexibility options, and the full set of stakeholder criteria. Studies that address these dimensions together, while also considering Bonaire's climate conditions, socio-economic context, and societal acceptance, are still missing. This lack of holistic research represents a major knowledge gap that needs to be addressed to support Bonaire's transition to 100% renewable energy. To fill this gap, the objective of this research is to design a fully renewable electricity system for Bonaire that evaluates the transition against stakeholder socio-economic criteria and explores generation and flexibility options beyond storage, including demand-side measures. This objective leads to the central research question, which guides the analysis and frames the evaluation of potential pathways for Bonaire's energy transition:

How can a fully renewable electricity system be designed for Bonaire that ensures reliability, affordability, sustainability and energy security?

Chapter 4: Methodology

As described in Section 1.4, this research applies a modelling-based approach to design a fully renewable electricity system for Bonaire. This chapter identifies the sub-questions that provide the inputs for the model and explains how each is addressed. Based on these inputs, the model is used to develop scenarios in which different flexibility options are compared to determine the cost-optimal system design. The scenarios are then evaluated against the stakeholder criteria of sustainability, reliability, affordability, and energy security, presented in 2.3.5. Finally, the chapter outlines how uncertainties and methodological limitations are accounted for through scenario-based analysis.

4.1 Sub-Question and research methods

To address the main research question, it is divided into several sub-questions. Each sub-question focuses on a specific element of the energy transition and flexibility, contributing to the overall goal of facilitating Bonaire's renewable energy transition in a way that is reliable, sustainable, affordable, and secure. Each sub-question is answered using methods tailored to its focus.

The first sub-question examines the transition of the supply side from diesel generators to renewable energy sources. It aims to analyze the potential of different renewable technologies for Bonaire, including options for flexible generation. This will be addressed through a literature review of renewable technologies combined with secondary data analysis of Bonaire-specific conditions, such as operational data from WEB (e.g., annual wind and solar production statistics) and resource assessments. A literature review will be used to assess the environmental impacts of feasible technologies for Bonaire, ensuring that selected options align with the island's land-use constraints and climate goals. The outcome identifies which renewable technologies can realistically be deployed and provides the supply-side input for the system model.

1. ***What renewable energy sources are technically feasible for Bonaire's electricity system and considering environmental sustainability?***

The second sub-question examines the potential of demand-side flexibility by analysing consumer types, their share of total electricity use, and the island's load patterns. The aim is to identify opportunities to shift demand and evaluate how much consumers can adapt their usage during peak hours. This will be assessed through secondary analysis of load profiles and sectoral consumption data, complemented by a survey of Bonaire's residents conducted via WEB's communication channels. Together, these methods determine the demand-side flexibility options that can be included in the scenario analysis.

2. ***What is the potential of demand-side flexibility in Bonaire's electricity system, based on consumer load patterns and willingness to adapt?***

The third sub-question addresses energy storage, which plays a crucial role in providing flexibility within a renewable-based system. It focuses on the ability of storage to cover peak demand and supply backup during periods of low renewable generation. To answer this, a literature review will compare centralized and decentralized technologies, assessing storage duration, discharge capacity, and suitability for Bonaire's system. Case studies from other island systems will support this analysis by highlighting feasible options under similar conditions. The results define the storage solutions that are incorporated into the model as flexibility scenarios.

3. ***What energy storage solutions are suitable for Bonaire's electricity system, considering centralized and decentralized applications as well as the required storage duration and capacity?***

By linking the supply solutions from Sub-question 1 with the demand and storage solutions from Sub-questions 2 and 3, this sub-question develops a cost-optimal pathway for Bonaire's transition that combines renewable energy with flexibility mechanisms to ensure reliable supply. Grid expansion is included as a long-term flexibility option. The analysis is conducted using a Linear Optimal Power Flow (LOPF) model developed in PyPSA, which integrates renewable generation, demand, and storage within system constraints. Scenario analysis is applied to test each flexibility option independently, including DSM, different storage technologies, and supply-side flexibility, resulting in alternative cost-optimal system configurations of technologies and capacities. The model relies on inputs from WEB's technical drawings, system planning data, demand data, and relevant literature for cost and efficiency assumptions. Optimization is performed with the Gurobi solver under academic license, producing cost-optimal designs for the different scenarios.

4. ***What is the cost-optimal electricity mix for Bonaire that integrates renewable energy sources and flexibility options to ensure reliability?***

Finally, to answer the main research question, the results of the scenario analysis are evaluated against the stakeholder criteria of reliability, affordability, energy security, and sustainability (2.3.5). Sub-question 4 already provides the cost-optimal and reliable system design, but the discussion extends this by assessing how different flexibility strategies perform across all four dimensions. Reliability is measured by the system's ability to consistently meet demand, including during peak stress or low renewable output. Affordability reflects both capital investments and operational costs. Energy security considers resilience to long-term disruptions and securing prices it doesn't threaten economic stability , while sustainability addresses greenhouse gas emissions, land use, and broader ecological impacts. By comparing the flexibility strategies against each other on these criteria, the analysis goes beyond cost optimization and reveals the trade-offs between reliability, economic feasibility, supply security, and environmental responsibility. This integrated evaluation concludes with strategic recommendations on how Bonaire can implement a fully renewable electricity system that is not only cost-effective and reliable, but also secure and sustainable.

4.2 Modelling framework

This section explains the cost-optimal model that will be used to test different flexibility options, producing system configurations that meet demand reliably at the lowest cost. The model itself optimizes only for cost and reliability, while sustainability and energy security are assessed in the discussion of the model results.

The electricity system of Bonaire is modelled as a Linear Optimal Power Flow (LOPF) problem using the open-source toolbox PyPSA (Python for Power System Analysis). PyPSA is widely used in both research and practice to model, simulate, and optimize electricity systems, offering efficient routines for power flow analysis, system operation, and investment planning (PyPSA: Python for Power System Analysis, n.d.). In PyPSA, generators, storage, transmission, and demand are represented on a network, and the least-cost system dispatch is solved while allowing capacity expansion within technical limits.

LOPF is a linear programming formulation of the power flow problem that identifies the least-cost way to operate and expand a power system while ensuring compliance with technical constraints (Belaid et al., 2025). In this study, it is implemented using the DC load flow approximation (also referred to as Linear OPF), where bus voltage magnitudes are assumed constant, line resistances are neglected, and only active power flows are represented. While this simplification omits nonlinear effects such as transmission losses and voltage variations, it significantly improves computational tractability without compromising the essential features required for long-term system planning. For this reason, LOPF remains the standard method in long-term capacity expansion studies, enabling joint optimization of investment and dispatch decisions across multiple hours and scenarios (Stott et al., 2009; Taheri et al., 2024).

4.2.1 Mathematical model: Power system formulation

Within this framework, PyPSA represents generation, storage, transmission, and demand on a network and solves for least-cost dispatch and, where allowed capacity expansion subject to physical limits (PyPSA: Python for Power System Analysis, n.d.). The mathematical linear problem defined here corresponds directly to the formulation that PyPSA applies in practice.

he objective of the model is to minimize the total cost of Bonaire's electricity system while ensuring demand is met within the island's technical and resource limitations. This combines investment costs for new assets with operational costs of dispatchable units. In practice, the model determines both which capacities should be built and how the system should be operated at an hourly level to supply electricity at the lowest cost.

The decision variables represent the main system components:

- Generation: installed capacity and hourly dispatch, limited by availability and technical constraints.
- Storage: installed power and energy capacity, along with hourly charging, discharging, and state of charge, subject to efficiency and capacity limits.
- Transmission: installed line capacities and hourly flows, with reinforcement only permitted where technically realistic.

The optimization is solved using Gurobi with the Simplex algorithm, which efficiently handles large-scale linear problems. This method systematically explores feasible system configurations and identifies the least-cost solution while maintaining computational efficiency and robustness.

To ensure technical feasibility, the model enforces a set of physical and operational constraints. Supply and demand must balance at every bus and every hour, renewable and flexible units are capped by their availability or ratings, storage operation is limited by energy and power capacities, and transmission flows are restricted by thermal ratings. Power flows are modelled using the DC load flow approximation, which links flows to bus voltage angle differences while maintaining consistency with Kirchhoff's laws.

By combining cost-minimization with these constraints, the model produces results that are both economically optimal and technically consistent with grid operation. Outputs include the least-cost mix of capacity additions, required grid reinforcements, and the dispatch of all resources across time. The full mathematical formulation, including the objective function and constraints, is not reproduced here, as the model follows the formulation provided in the PyPSA documentation (*PYPSA: Python for Power System Analysis — PYPSA: Python for Power System Analysis*, n.d.).

4.2.2 Model inputs and representation in PyPSA

The Linear Optimal Power Flow (LOPF) model in PyPSA requires inputs for each element of Bonaire's electricity system: generation, storage, transmission, and demand. These inputs provide the technical, temporal, and cost parameters that the optimizer uses to evaluate both capacity expansion and operational decisions.

In PyPSA, the **network** consists of connected buses. A bus represents a node in the electricity system where generation, demand, storage, and transmission elements are linked. Each bus functions as a balance point, where electricity inflows from generation or imports must equal outflows to demand, storage charging, or exports. In practice, buses correspond to physical assets such as substations, switching stations, or power plants, and together they form the overall network. For Bonaire, the network is simplified to the 30 kV backbone and the 12 kV primary distribution system. At the 30 kV level, the Morotín Wind Park connects to the Contour Global site, which also hosts the diesel units, the utility-scale solar PV park, and the existing battery. From Contour Global, two 30 kV lines connect to the main substations at WEB Nobo (Kralendijk) and Rincon. These substations in turn connect to the 12 kV distribution and switching stations, including Den Laman, Industrie Terrein, and Mariadal. Each of these locations is represented in PyPSA as a bus with demand, generation, and storage elements attached if appliable. This abstraction captures the essential interactions between generation, storage, and the main transmission corridors, while deliberately excluding finer details such as low-voltage feeders, reactive power and voltage control, protection schemes, and N-1 security analysis.

Transmission is represented by lines that connect the buses. Each line is parameterized by its resistance and reactance, which determines how flows are distributed under the DC load flow approximation, and by its nominal thermal rating, which sets the maximum power transfer. In the Bonaire system, these correspond to the 30 kV backbone cables and the 12 kV primary distribution feeders. All transmission lines are defined as extendable. This allows the optimizer to reinforce line capacity if it is cost-effective for integrating additional renewables or accommodating demand growth. The costs of reinforcement are expressed as total capital values in USD per megawatt.

Generation units are attached to buses as either dispatchable or variable resources. Each generator is defined by its installed nominal capacity, which can be fixed for existing assets or extendable if additional capacity can be built. Hourly availability profiles constrain the maximum dispatch of variable renewables, using solar and wind time series derived from WEB's 2024 data. In the base model, only existing capacity is represented: 24 MW of wind at Morotín and 6 MW of solar at Contour Global. Both are extendable, so the optimizer can add capacity where cost-effective. Other generation technologies are excluded from the base model. Their technical feasibility is first analysed in earlier chapters, and only those identified as suitable are introduced later in the scenario analysis. Marginal costs are set at zero for renewables, while dispatchable backup units such as biodiesel carry positive marginal costs to capture ongoing fuel expenditures.

Storage is represented in PyPSA as Storage Units, combining power capacity (MW), energy capacity (MWh), and operational constraints. In the base model, storage consists only of the existing lithium-ion battery at Contour Global, with 14 MW power and 9 MWh energy. This unit is modelled as fixed, with no capital cost, round-trip efficiency, and a non-cyclic state of charge (i.e., it does not need to end the month at the same charge level it started). New storage technologies can be added at Contour Global. Their potential is first assessed in the storage analysis, and only those identified as technically feasible are introduced in the base case. For scenario analysis storage will be added at substations, distribution stations and switching station as extendable units. Each storage option is defined by its installed power capacity and duration, from which energy capacity is derived. Charging and discharging efficiencies reflect round-trip losses, and investment costs are converted into total cost (USD/MW). Marginal costs are set to zero.

Demand is represented as fixed hourly loads attached to substations and switching stations. These loads are distributed across buses according to WEB's 2024 dataset, ensuring that demand follows realistic spatial and temporal patterns. For 2030, demand is scaled along two trajectories: a moderate growth scenario of +3% annually (historical trend) and a high-growth scenario of +6% annually, with growth distributed according to planned projects. In the base model, demand is inelastic. Demand-side flexibility is excluded at this stage but introduced later in scenarios, based on load profiling and survey results on willingness to participate in DSM programs.

4.2.3 Temporal resolution

The model targets the planning year 2030 and uses 2024 hourly load data at the substation level, which are scaled to 2030 based on forecasted demand growth. Instead of simulating the entire year, the analysis focuses on September 2030, which is selected as the stress month. The underlying assumption is that if the electricity system can reliably meet demand during this period, it will also be sufficient to meet demand throughout the rest of the year. Modelling at an hourly resolution captures daily variations in both demand and renewable generation, which is crucial for assessing the performance of flexibility options such as storage and demand-side management, as well as for determining the optimal configuration of dispatchable and variable generation sources. By concentrating on the stress month, the model examines system behaviour under the most challenging conditions, providing a strong basis for evaluating the role of flexibility in enabling a fully renewable electricity system.

4.3 Conceptual model representation

The mathematical formulation and inputs described previously are summarized visually in the conceptual model diagram (figure 7), which illustrates how the optimization problem is structured in practice. The diagram translates the equations into a flow of information: from fixed inputs, through decision variables and constraints, to the objective function and resulting outputs.

On the left side, the inputs are the exogenous parameters provided to the model. These include the hourly demand time series, renewable resource availability, cost assumptions for each technology, and the technical characteristics of the transmission grid and storage systems. These values are fixed and cannot be changed by the optimizer.

At the centre, the decision variables capture the choices made by the optimizer. These include how much new generation capacity to build and how to dispatch existing units' hour by hour, what type and amount of storage to install and how it should be charged and discharged, and how much power flows across the transmission network, including potential reinforcements of line capacities.

The constraints ensure that all solutions are technically and physically feasible. They enforce supply–demand balance at every bus and every hour (Kirchhoff's Current Law), ensure that line flows respect the physical laws of the grid (Kirchhoff's Voltage Law), and limit generators, storage, and transmission to their respective capacities and availability. Storage units are further constrained by round-trip efficiency losses and state-of-charge dynamics.

Above these elements lies the objective function, which minimizes total system cost. This includes investment costs for new generation, storage, and transmission, as well as operating costs for dispatchable technologies.

On the right side, the output represents the optimization results. These include the least-cost mix of generation and storage technologies, required transmission reinforcements, the hourly dispatch of all resources, and the total system cost under each scenario.

In this way, the conceptual diagram provides a simplified but complete representation of how the optimization model operates: inputs feed into the decision space, constraints maintain feasibility, the objective drives cost minimization, and the outputs reveal a technically consistent and economically optimal design for Bonaire's transition to 100% renewable electricity.

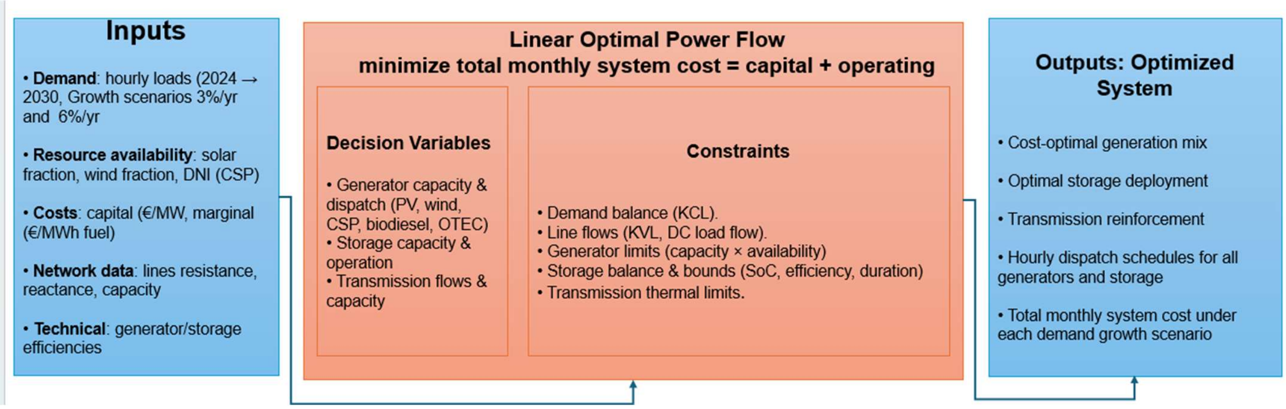


Figure 7: Conceptual representation of the optimization model for Bonaire's electricity system (own elaboration)

4.4 Validation, limitations and mitigation

Validation is embedded throughout the research process to ensure findings are robust and grounded in both empirical data and local context. For renewable generation and storage (SQ1 and SQ3), literature insights are cross-checked with operational data from WEB, such as production statistics and technical documentation, ensuring that global knowledge aligns with Bonaire's actual performance. For demand-side flexibility (SQ2), a survey of households and large consumers validates assumptions about willingness to participate in DSM programs. This complements secondary analysis of load profiles and sectoral demand, providing empirical confirmation of flexibility potential. At the system level (SQ4), validation is achieved through scenario testing, in which different combinations of generation, storage, and DSM are simulated under alternative assumptions of demand growth and technology costs. This approach strengthens confidence in the feasibility and resilience of the proposed solutions.

Each methodological step has limitations. The use of a Linear Optimal Power Flow (LOPF) model simplifies grid behavior by excluding nonlinear dynamics such as reactive power flows and voltage fluctuations. Although this reduces precision, it remains sufficient for the purpose of comparing flexibility options, which is the central aim of this study. Its validity is reinforced through calibration with operational data and robustness checks across multiple scenarios. Literature reviews risk becoming outdated or narrow, which is mitigated by drawing on both peer-reviewed and grey literature. The survey method carries risks of limited participation and representativeness; these are addressed through stratified sampling, pretesting of questions, and dissemination via multiple WEB communication channels. To ensure reliability, different levels of DSM potential are also tested in the scenario analysis. Secondary data analysis may suffer from gaps in relevance or quality, but targeted access to WEB datasets enables cross-checking and validation. Finally, uncertainties in demand growth, technology costs, and renewable availability cannot be fully eliminated, but by explicitly incorporating them into scenario analysis, the study ensures that conclusions focus on the relative impact of flexibility options rather than on exact capacity forecasts.

Chapter 5: Renewable energy potential

This chapter aims to answer the first sub-question: ***What renewable energy sources are technically feasible for Bonaire's electricity system and considering environmental sustainability?***

ContourGlobal currently operates 34.96 MW of diesel thermal generation, 11.1 MW of wind power, and a 6 MW solar PV farm (ContourGlobal, 2025). Plans are also in place to expand wind capacity to 24 MW by 2026 (Elektriciteit en Water- en Energiebedrijf Bonaire, n.d.). While wind and solar are at present the main renewable sources on the island, this chapter explores additional technologies that could enhance system flexibility. Each technology is assessed in the context of Bonaire's climate and geography, with attention to technical feasibility, resource availability, and environmental impact. The environmental dimension focuses primarily on carbon footprint and land use, while other significant impacts are discussed where relevant. The purpose of this evaluation is to identify renewable options most suitable for Bonaire's long-term energy strategy and to ensure a reliable, environmentally sustainable, and secure electricity supply for the island.

5.1 Renewable energy technologies

Figure 8 categorizes Renewable Energy Technologies (RETs) into six main groups based on their primary energy sources (Tran & Smith, 2017). Together, these sources illustrate the diversity of renewable options. In the following sections, this structure is used to discuss each technology, and their feasibility is assessed in the specific context of Bonaire's climatic and geographic conditions.

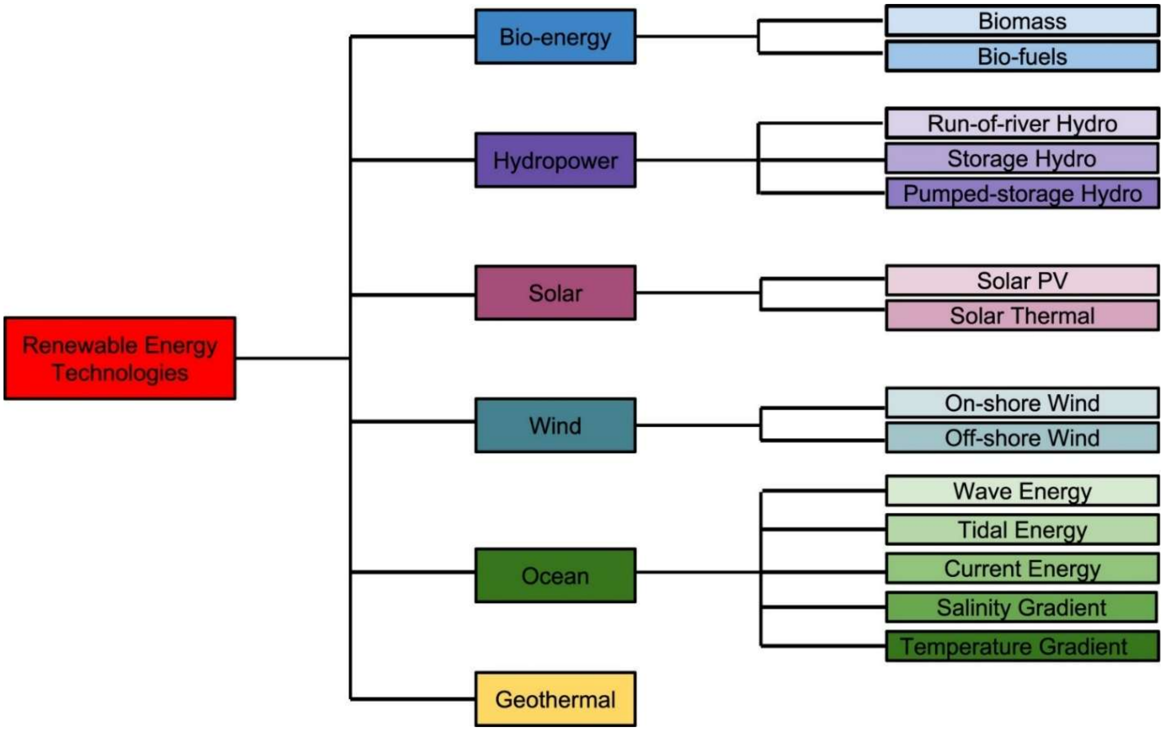


Figure 8: overview of renewable energy technologies (Tran & Smith, 2017)

Before examining Bonaire's specific resource availability, it is useful to place the island's options in a global and regional context. Solar and wind are the largest renewable resources worldwide, each with a technical potential well above current global energy demand (Krishnan, 2023). Their importance is also reflected at the regional scale. Figure 9 shows renewable energy applications across the Caribbean (Brecha et al., 2021), where solar PV and wind power dominate due to favorable climatic conditions. Bonaire's existing system already reflects this pattern, with both resources forming the backbone of local renewable generation.

Other technologies, including hydropower and geothermal, are present on some Caribbean islands, but their viability depends on specific site conditions such as reliable freshwater flows or geothermal reservoirs. Since such resources are highly location-dependent, their potential on Bonaire must be assessed in the context of the island's particular geological and hydrological characteristics.

Figure 9: Map of the Caribbean showing renewable energy potential by country, including geothermal, solar photovoltaics, wind, and hydropower resource (Brecha et al., 2021).

5.2 Bonaire current renewable energy technologies

As previously noted, wind and solar PV currently form the backbone of renewable energy generation on Bonaire. This section evaluates their feasibility to meet future demand growth and examines the limitations of relying on them as the sole resources without continued dependence on diesel generators.\

5.2.1 Feasibility of wind energy on Bonaire

According to data from the Global Wind Atlas, the average annual wind speed on Bonaire is approximately 8.9 m/s at 50 m hub height. This corresponds to IEC Wind Class I (defined as > 8.5 m/s). This positions Bonaire among the highest-quality onshore wind sites worldwide, with the potential for high-capacity factors, low intermittency, and predictable generation profiles, making wind one of the island's most promising renewable resources (Lledó et al., 2019).

The island's main wind asset is the Morotin Wind Park on the northeast coast, consisting of twelve Enercon E-44 turbines rated at 900 kW each, for a total installed capacity of 10.8 MW (Sun et al., 2016. In 2024, the park generated 25,177 MWh, corresponding to a capacity factor of 26.6 % (figure 10). This lower capacity factor reflects downtime from two turbines being offline for part of the year rather than limitations in the wind resource. The Sorobon wind turbine (Enercon E-33, 330 kW) produced 746,960 kWh in 2024 (11 months recorded), corresponding to an adjusted capacity factor of 27.4 %.

Even with partial downtime, both installations outperform the 2023 EU onshore average capacity factor of 24 % and match closely with the overall EU wind fleet average of 25 %, though they remain below the EU offshore average of 34 %. Expansion to 24 MW will leverage Bonaire's strong wind profile, positioning wind as a cornerstone of the island's clean energy transition (Bonaire.nu, 2024).

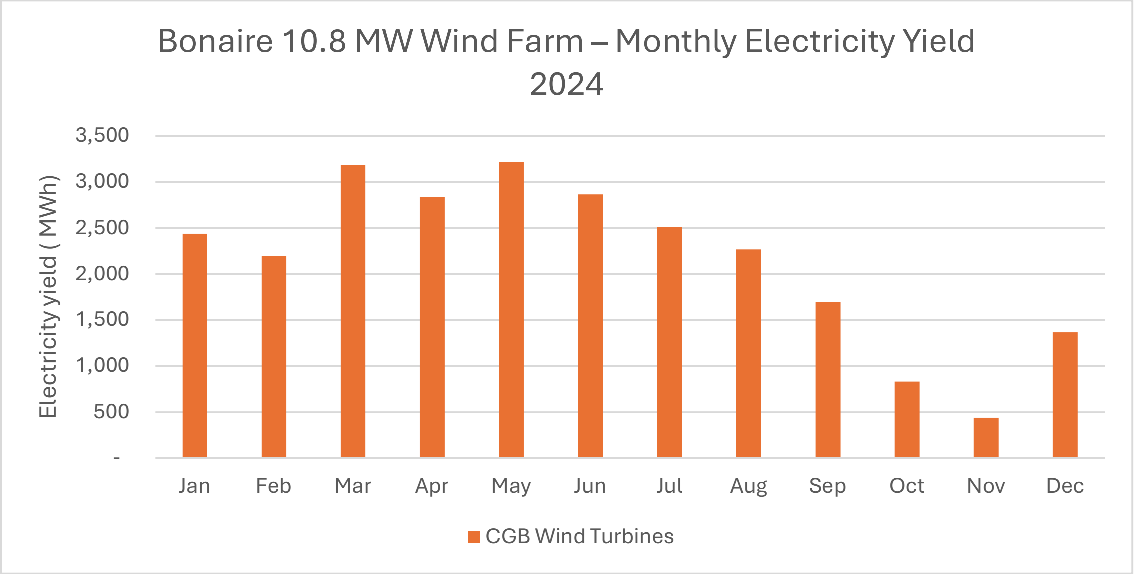


Figure 10: Monthly electricity yield of the 10.8 MW wind park in Bonaire for 2024, showing higher generation during March–May and lower outputs in October–November (based on data collected from WEB Bonaire).

5.2.2 Trade-offs between onshore and offshore wind energy

Onshore wind is preferred for Bonaire due to its proven feasibility, relatively low costs, and straightforward integration into the existing grid. The island's strong and consistent trade winds, particularly along the eastern coast, qualify as IEC Class I conditions, comparable to offshore sites in terms of high-capacity factors and predictable output (Chadee & Clarke, 2013; Schelleman et al., 2016; Lledó et al., 2019).

Although offshore wind can offer somewhat higher and steadier wind speeds, the difference relative to Bonaire's already exceptional onshore resource is modest. By contrast, offshore development entails much higher costs and technical complexity, including marine construction, subsea cabling, and extensive maintenance. Global studies show that offshore levelized costs of electricity remain 40–60 percent above onshore values despite ongoing reductions (Tumse et al., 2024). For a small island system, these factors make offshore far less feasible than expanding onshore capacity.

The main constraint for onshore expansion is land availability, which may limit the scale of future wind development and necessitate complementary solutions. This trade-off is considered further in Section 5.9. Overall, onshore wind remains the most practical, cost-effective, and strategic option for Bonaire's renewable energy future, provided spatial constraints are carefully assessed.

5.2.3 Feasibility of solar PV energy on Bonaire

Solar potential is measured by two key indicators: Global Horizontal Irradiation (GHI), which captures all sunlight falling on a flat surface, and Direct Normal Irradiation (DNI), which measures only direct sunlight. PV systems mainly rely on GHI, while Concentrated Solar Power (CSP) requires high DNI (Giaconia & Grena, 2021). Bonaire's resource levels place it among the best solar locations worldwide, with an average of about 2,253 kWh/m²/year of GHI and 2,066 kWh/m²/year of DNI (Solargis, n.d.). These values confirm excellent feasibility for PV deployment and sufficient resource for CSP as well.

Based on data from WEB Bonaire, the island's 6 MW solar PV plant produced 9,657 MWh in 2024 (see figure 11), corresponding to a capacity factor of 18.3%. This performance is slightly above the global utility-scale PV average of 17.4 percent in 2024 (Statista, 2025) and far higher than northern European countries such as the United Kingdom and the Netherlands (Mearns, 2015). Where average PV capacity factors remain in the range of 9–11 %. These outputs confirm that Bonaire's PV is globally competitive, making solar PV a cornerstone of the island's renewable energy transition.

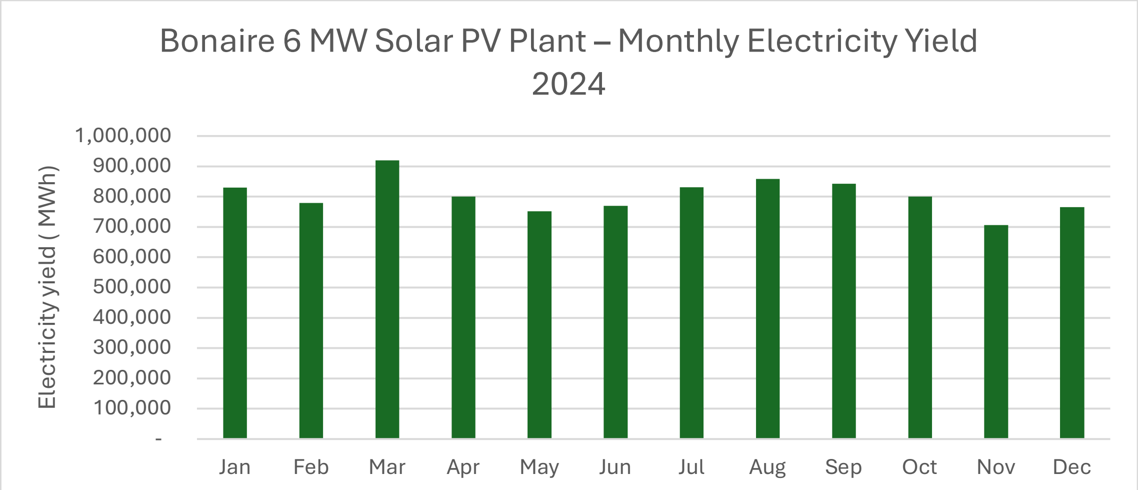


Figure 11: Monthly electricity yield of the Bonaire 6 MW PV solar plant in 2024, showing seasonal variation with the highest output in March and the lowest in November (based on data collected from WEB Bonaire).

5.2.4 Feasibility of a renewable system based solely on wind and solar

As concluded in the previous sections, onshore wind and solar PV will form the backbone of Bonaire's energy transition. The key question is whether these two resources alone can provide a system that is cost-efficient, reliable and environmentally sustainable over the long term.

Appendix C2 shows that wind speeds on Bonaire vary seasonally, with indices ranging from about 0.80 in November (~7.1 m/s) to 1.14 in June (~10.2 m/s) (Global Wind Atlas, n.d.). Output is highest between March and June, coinciding with seasonal wind peaks, and lowest in October–November when wind speeds fall to their annual minimum. On a daily scale, wind is typically strong just after midnight and remains above average into the morning, then declines through the afternoon before recovering in the late evening. This creates a diurnal profile that complements solar output. Appendix C3 (PVGIS, European Commission, 2016) shows that solar irradiance follows a stable annual pattern, with output peaking during the day and falling to zero at night. November is an exception, when tropical weather systems cause recurring dips in irradiation. Solar's key limitation is its mismatch with evening demand, as output declines around 18:00 precisely when consumption rises.

In combination, wind and solar exhibit clear synergies. Solar covers daytime demand at low cost, while nighttime winds provide an important counterbalance when PV is unavailable. Nevertheless, important limitations remain. Wind output drops significantly in October–November and storm conditions can suppress production further. At the same time, solar irradiance also dips during this period, leaving both resources weak when demand is still substantial. Thus, while wind can complement solar, the pair alone cannot guarantee year-round stability.

To address these gaps, balancing measures are required. Options include energy storage, flexible generation, and demand-side management. Batteries can provide short-term coverage but remain expensive at large scale. Overbuilding wind and solar capacity could also bridge shortfalls, but this would raise costs, increase land requirements, and intensify material and environmental impacts.

For Bonaire, where land is limited and environmental considerations are critical, reliance on wind and solar alone may not be sufficient. A sustainable long-term system will likely require a combination of wind, solar, storage, and complementary dispatchable energy sources to ensure stability, affordability, and environmental responsibility.

5.3 Concentrated solar power

Concentrated solar power (CSP) systems use mirrors or lenses to concentrate direct normal irradiance (DNI) onto a heat transfer fluid, such as molten salt or synthetic oil, which can be used immediately to generate steam or stored in thermal energy storage (TES) for later electricity production (Gauché et al., 2017). This makes CSP a dispatchable renewable technology capable of supplying electricity after sunset or during cloudy periods. With TES, CSP plants can also provide ancillary grid services such as frequency regulation, voltage support, and reserve capacity (Giaconia & Grena, 2021).

Although CSP is more capital-intensive than PV, its system value lies in delivering firm capacity without relying on costly large-scale batteries. PV typically provides the cheapest daytime electricity at about 3 ¢/kWh, while CSP with TES costs around 6 ¢/kWh. However, CSP is more cost-effective than pairing PV with equivalent battery storage for evening and night supply (Petrollese & Cocco, 2016). Recent studies confirm that at solar penetration levels of 20–30 percent, CSP with TES becomes competitive, producing electricity up to 16 percent cheaper than PV plus batteries, and at higher shares it can reduce system costs by as much as 65 percent (Miron et al., 2023).

Case evidence reinforces this potential. In Chile, a PV–CSP hybrid with 13 hours of TES achieved an LCOE of 53 USD/MWh, well below the 86 USD/MWh of a comparable natural gas plant, while providing fully dispatchable output (Catalina Hernández Moris et al., 2021). Globally, CSP costs declined by roughly 50 percent during the 2010s, and projects co-located with PV have shown higher capacity factors and improved economics (Adib et al., 2021).

Overall, PV and CSP are not substitutes but complementary. PV excels in delivering low-cost daytime electricity, while CSP with TES extends renewable supply into the evening and night. Hybrid PV–CSP systems optimize land use, reduce storage needs, and improve overall reliability (Petrollese & Cocco, 2016). For Bonaire, where DNI reaches 2,066.3 kWh/m^2/year (Solargis, n.d.), CSP represents a technically feasible and strategically valuable option. While PV will remain the least cost backbone of the energy transition, CSP could play a key role in reducing diesel dependence and ensuring a reliable and sustainable renewable energy system.

5.4 Bioenergy

Unlike wind or solar, bioenergy can be stored and used when required, making it a more predictable and dispatchable energy source. Bioenergy technologies convert biomass into electricity, heat or fuels. The two main routes are combustion or gasification, which generate power and heat, and biochemical and thermochemical processes that produce biofuels, such as ethanol and biodiesel. These fuels can be used in combustion engines, and biodiesel can be blended with or replace fossil diesel in generators.

5.4.1 Bio-Energy feasibility on Bonaire

At present, Bonaire does have no biomass combustion plants or biofuel production facilities Water- en Energiebedrijf Bonaire N.V. et al., 2015). Local feedstock availability is very limited. The dry climate, low rainfall and scarce arable land severely constrain the potential for cultivating energy crops such as wood, grass, or oil-bearing plants. Large-scale biomass production would require substantial water resources and agricultural inputs, which are neither practical nor sustainable under local conditions.

Microalgae present a more sustainable and locally adapted alternative for Bonaire. They combine high productivity with flexibility in cultivation and environmental co-benefits. Unlike terrestrial crops, they can grow in saline, brackish, or wastewater. Avoiding competition with food production while achieving much higher biomass and lipid yields per unit area (Slade & Bauen, 2013). Cultivation in photobioreactors further enhances growth rates and enables efficient CO_2 capture, making microalgae valuable for both renewable energy generation and climate mitigation (Omokaro et al., 2025). Their biomass can be processed into biodiesel, biogas, bio-oil (Amaral et al., 2020). Pilot projects by Wageningen University & Research already explore algae cultivation on Bonaire as part of circular economy and CO_2 reduction strategies (Pionieren Met Microalgen Op Bonaire | NWO, n.d.). Initiatives under the island's "Blue Destination" vision promote algae farming as an innovation that integrates ecological conservation with renewable energy (Algenfarm Past in Blue Destination-ambitie Bonaire, 2020). Despite this potential, costs remain a major barrier: harvesting, drying and oil extraction are highly energy- and cost-intensive (Slade & Bauen, 2013). Photobioreactors deliver higher yields but are capital-intensive, whereas cheaper open ponds face contamination risks and lower productivity (Omokaro et al., 2025).

Macroalgae, particularly the sargassum seaweed that seasonally accumulates on Bonaire's shores, offers a more immediate opportunity. Anaerobic digestion of sargassum can generate biogas while reducing coastal pollution, turning an environmental burden into a renewable resource. This approach aligns with Bonaire's circular economy goals and is currently under investigation through Wageningen University's

BONCIRC project, which focuses on valorizing coastal biomass waste for clean, dispatchable energy (Sustainable and Circular Organic Waste and Sargussum Management on Bonaire, n.d.).

As a result, both biomass-based electricity generation and biodiesel production on Bonaire would currently depend on imported feedstock or finished fuels. Importing biodiesel represents the most practical and immediately actionable pathway, as it is fully compatible with Bonaire's existing generator fleet and can be used with minimal infrastructure adjustments (Marine GenSets, n.d.). Developments in Curaçao are particularly relevant: a large-scale renewable diesel facility is planned, designed to process vegetable oil into approximately 13,000 barrels of renewable diesel per day (Eleonora, 2022). Since Curaçao already functions as Bonaire's primary fossil fuel supplier, it is well positioned to also become a regional exporter of renewable diesel, providing Bonaire with a feasible route to reduce its reliance on conventional fossil fuels. Recent reporting further underlines this ambition: Curaçao is increasingly positioning itself as a future biofuel export hub for the Caribbean, with ongoing investments in renewable diesel and related facilities (Antilliaans Dagblad, 2023).

5.4.2 Bio-energy conclusion

Bioenergy, in the form of imported biofuel and locally produced biogas from sargassum, can play a supportive role in Bonaire's transition to 100% renewable electricity. While it cannot serve as the island's primary energy source, due to emissions, reliance on imports, and the high costs of local production, its dispatchable nature makes it an effective complement to variable renewables such as wind and solar. By covering peak demand and providing backup during periods of low renewable output, bioenergy can reduce the need for oversized generation or expensive storage systems. In the short term, importing biofuels offers the most practical transitional option. They are fully compatible with Bonaire's existing generator fleet and can be integrated with minimal adjustments. Curaçao provides concrete opportunities for supply, with both the large-scale renewable diesel facility and Energis's waste-to-biofuel operations positioning themselves as regional exporters. In the longer term, locally sourced solutions such as sargassum-derived biogas and microalgae cultivation could become viable alternatives. Ongoing pilot projects already explore these pathways, which not only contribute to renewable energy production but also align with Bonaire's circular economy ambitions and environmental management strategies.

5.5 Hydropower

Hydropower converts the kinetic or potential energy of water into electricity by driving turbines (Egré & Milewski, 2002; Killingtveit, 2018). It is one of the most mature renewable technologies, typically implemented as run-of-river, reservoir-based, or pumped-storage systems. The feasibility of these approaches is strongly determined by local climate and geography. Run-of-river plants require steady year-round flows and elevation differences, while reservoir systems store water for flexible generation but depend on large and consistent freshwater resources and land availability. Pumped storage, often used as an energy storage solution, requires two reservoirs at different elevations and reliable water supply.

On Bonaire, however, none of the main hydropower technologies are feasible. The island has no permanent rivers or streams, and surface water is limited to temporary runoff channels that only carry water after heavy rainfall (Witteveen+Bos Raadgevende ingenieurs B.V., Deventer, 2024). Annual precipitation averages just 500 mm, much of which is lost to evaporation in the island's arid climate and shallow soils (Slijkerman et al., 2019). Freshwater availability is already limited and relies heavily on costly seawater desalination. Moreover, Bonaire lacks natural lakes and the elevation needed for reservoirs or pumped-storage schemes. These geographic and climatic constraints rule out hydropower as a viable option for the island's renewable energy transition.

5.6 Ocean energy

Ocean energy refers to a diverse set of renewable technologies that harness waves, tides, currents, salinity gradients, and thermal differences in the ocean to generate electricity. Although most are still in research or early commercialization, they offer significant potential due to their predictability, sustainability, and global availability in coastal regions (Su et al., 2025). Each marine energy technology depends on specific geographic and environmental conditions to be technically and economically viable, and in most cases Bonaire's characteristics rule them out.

Wave energy captures the motion of surface waves created by wind and shows strong potential in coasts with energetic wave climates (N. Khan et al., 2017). However, in Bonaire the wave climate is weak: Caribbean buoy data from 2009–2019 show average wave power densities of only 10–14 kW/m, well below the 20–35 kW/m generally required for commercial viability (Gu & Li, 2022; Bethel, 2021). Combined with the high capital and maintenance costs of offshore equipment, wave energy is not a feasible option.

Tidal energy exploits the gravitational pull of the moon and sun, either through barrages that trap tidal range or underwater turbines in tidal streams (M. Lewis et al., 2017). For effective generation, tidal barrages typically need ranges greater than 4 m, and turbines require stream velocities of 2–3 m/s in narrow straits. Bonaire's tidal range is less than 1 m, and the island has neither narrow straits nor high-velocity tidal currents (Gijsman et al., 2021), excluding this resource.

Ocean current energy uses submerged turbines to harvest steady horizontal flows, offering potential baseload power but still facing challenges with anchoring, durability, and offshore infrastructure (Sanchez et al., 2021). While Bonaire lies near the North Brazil Current, the flow is located far offshore, making the technology expensive.

Salinity gradient energy relies on the chemical potential between freshwater and seawater at river mouths (Manikandan et al., 2024). Since Bonaire has no rivers, estuaries, or deltas, the island lacks the salinity differences needed, ruling out this technology entirely.

Ocean Thermal Energy Conversion (OTEC) leverages the temperature difference between warm surface water and cold deep water in tropical oceans (Lewis et al., 2011). Closed-cycle systems circulate low-boiling-point fluid such as ammonia, while open-cycle systems use seawater directly, producing freshwater as a by-product. Bonaire offers ideal conditions: the island maintains a year-round thermal gradient greater than 22 °C, and deep waters are located within 10 km of shore, making cold-water pipe installation technically feasible (Herrera et al., 2021; Ministerie van Economische Zaken & Thompson, n.d.; Schelleman et al., 2016b). Unlike other marine options, OTEC can deliver continuous baseload generation and simultaneously produce desalinated water, addressing two critical island needs. High infrastructure costs remain a barrier, but Bonaire's natural advantages make it one of the most promising candidates for future OTEC development.

5.7 Geothermal energy

Geothermal energy uses heat from the Earth's crust, typically accessible in volcanic or tectonically active regions. Electricity is generated either by using steam directly from reservoirs or by transferring heat to a secondary fluid in binary cycle plants. These systems can provide continuous baseload power but are geographically constrained and require high upfront investment, making potential highly site-specific (Sharmin et al., 2023).

Geothermal resources in the Caribbean are closely tied to island geology. Volcanic islands such as Dominica, Saba, and Nevis possess the highest potential due to active tectonics and high heat flow, making them prime candidates for geothermal development (Koon Koon et al., 2019). According to the Geological Survey of the Netherlands, Bonaire lies on an inactive volcanic arc and is primarily composed of reef limestone and coral formations, with only older volcanic rocks present at depth (Geologische Dienst Nederland, 2024). Such formations do not support high heat retention or the development of geothermal reservoirs. Geological studies confirm that Bonaire, together with Aruba and Curaçao, is tectonically stable and located outside the volcanic arc of the Lesser Antilles, where exploitable geothermal activity is concentrated (Hippolyte & Mann, 2009). As a result, Bonaire lacks the high geothermal gradients and reservoir conditions required for power generation.

5.8 Conclusion: Renewable energy technologies on Bonaire

This conclusion identifies the renewable technologies that are technically feasible for Bonaire's energy transition, considering the island's geographic conditions and resource availability. The assessment is guided by the criteria of reliability and reduced import dependence, while cost-effectiveness will be addressed in the cost-optimal modeling and environmental sustainability in the next section.

Wind and solar form the foundation of Bonaire's transition. The Morotin Wind Park and Sorobon turbine already perform above European benchmarks, and expansion to 24 MW would fully exploit the island's strong wind resource. Solar PV provides the cheapest daytime power, confirming its role as a cornerstone of the system.

Dispatchable technologies are needed to complement variable output. CSP with thermal energy storage, can extend supply into the evening more efficiently than PV with batteries. Bioenergy, though limited by scarce local feedstocks and reliance on imports, can provide targeted backup through biodiesel, while OTEC represents a longer-term strategic option given Bonaire's steep offshore profile and consistent thermal gradients, with the added benefit of freshwater co-production.

The most resilient pathway is therefore a hybrid portfolio of onshore wind and solar PV as the low-cost backbone, CSP with storage for dispatchable evening supply, bioenergy for backup, and OTEC as a long-term complement. This mix reduces fossil fuel dependence, avoids costly reliance on large-scale batteries, and balance's reliability with affordability.

5.9 Environmental impact assessment

In the next section, the selected technologies are evaluated against environmental sustainability criteria, with a focus on their carbon footprint during operation and their land-use requirements. These two dimensions are especially important for Bonaire, where the global goal of reducing greenhouse gas emissions intersects with the island's local challenge of scarce land competing with agriculture, tourism, and conservation. While cost and technical feasibility are crucial, the transition must also ensure that renewable energy development is environmentally sustainable and compatible with Bonaire's spatial and ecological constraints. A full LCA is beyond the scope of this thesis, but other impacts such as water use, biodiversity, material intensity, and local disturbance are acknowledged and discussed where they present significant risks or trade-offs. This ensures that the assessment remains focused on the island's most pressing sustainability concerns while not overlooking the broader environmental context.

5.9.1 Land use implications

Among all candidate technologies, OTEC is the most efficient. Most of its infrastructure is located offshore, with only a small onshore footprint for turbines, pumps, and heat exchanges (Rahman et al., 2022). This makes OTEC almost land neutral compared to land-based renewables, offering a strategic long-term advantage for an island where space is limited but ocean resources are abundant.

Wind power is one of the most land-intensive renewable options because turbines must be spaced five to ten rotor diameters apart, creating a large effective generation area. Globally, this translates to a median land use intensity of about 1,250 hectares per terawatt hour per year when spacing is considered, compared with only about 5 hectares per terawatt hour per year for the direct footprint of pads and access roads (Lovering et al., 2022) (Rahman et al., 2022). Much of the land between turbines can still be used for grazing or farming, but the visual and spatial impact is significant. On Bonaire, the island's 12 wind turbines, each rated at 0.9 MW, are spread along a 2.2-kilometer coastal stretch with about 200 meters between units. Although the direct footprint of each turbine is small, the required spacing creates an extended "generation corridor" that occupies a large share of the island's limited coastline. This constrains further expansion of onshore wind capacity in such a small and land-scarce setting.

Solar PV is more compact, with a global median land use intensity of about 36 hectares per terawatt hour per year (Rahman et al., 2022). Globally, utility-scale plants typically require around 1.4 to 4 hectares per MW (Lovering et al., 2022). On Bonaire, however, the 6 MW solar PV installation occupies just 5.5 hectares, or about 0.9 hectares per MW of installed capacity. This is well below the global average and highlights the high land-use efficiency of Bonaire's system. Unlike wind farms, where land within turbine spacing can often be used in parallel for grazing or farming, PV installations usually dedicate land exclusively to energy production. Local effects such as dust accumulation and vegetation loss may still reduce both ecosystem quality and panel efficiency.

CSP has a median land use intensity of about 41 hectares per terawatt hour per year, which is statistically similar to PV (Rahman et al., 2022). Depending on the design, CSP typically requires about 1.6 to 6.7 hectares per megawatt of installed capacity and must be built on large contiguous plots in areas with high solar irradiation. Like PV, CSP dedicates land exclusively to energy production. Although hybrid PV–CSP systems may improve overall land-use efficiency by sharing sites and enhancing grid reliability.

Dedicated energy crops are by far the most land demanding technology, with a median requirement of about 58,000 hectares per terawatt hour per year (Rahman et al., 2022). This makes them entirely impractical for a small island such as Bonaire. Cultivation also competes with food production and accelerates deforestation. Imported biofuels such as biodiesel are a different case. They can be used in the island's existing diesel generators without requiring new land or major infrastructure. For this reason, imported biofuels are effectively land neutral in Bonaire, although they still carry significant upstream land and environmental costs in producing regions.

5.9.2 Air emissions and pollution impacts

Wind, solar PV, CSP, and OTEC are effectively emission-free during operation, with their footprints arising mainly from manufacturing, construction, and decommissioning (Rahman et al., 2022). Wind stands out with one of the lowest lifecycle intensities at roughly 10–12 g CO_2/kWh, a figure that can be reduced further through recycling of turbine materials. Solar PV has higher embodied emissions, in the range of 32–82 g CO_2/kWh, mostly from energy-intensive silicon purification, but still an order of magnitude lower than coal. CSP falls slightly above PV, at 36–91 g CO_2/kWh, reflecting the production of molten salts and steel-heavy infrastructure. OTEC though offshore pipe manufacturing and installation contribute to its embedded footprint. Biomass is the clear outlier: combustion directly releases CO_2, CO, SO_2, NO_x, and particulates. While sometimes considered carbon-neutral because crops absorb CO_2 during growth, actual outcomes vary. Lifecycle emissions average 165 g CO_2/kWh, lowest when waste residues are used, and highest when dedicated crops are imported or cultivated intensively.

5.9.3 Additional environmental considerations

CSP is the most water-intensive, consuming 600–650 gallons per MWh, with leaks of salts or coolants risking pollution (Rahman et al., 2022). PV uses much less water, limited to panel cleaning. Wind has a negligible water footprint, while biomass is the most demanding at 20,000–50,000 gallons per MWh, often discharging nutrient-rich wastewater that drives eutrophication. OTEC, by contrast, uses no freshwater and in open-cycle systems can even co-produce drinking water, which is valuable for Bonaire, where land-based water resources are scarce and costly to produce through energy-intensive desalination.

Human health and disturbance impacts are most evident in wind and biomass. Wind turbines create aerodynamic noise, flicker, and glare, with offshore construction adding underwater noise. Biomass directly worsens air quality with particulates, SO_2, and NO_x, alongside strong odors. OTEC carries relatively few direct risks, though ammonia leaks in closed-cycle systems would cause

Biodiversity and ecological effects vary across technologies. PV and CSP farms disturb soil, vegetation, and habitats of reptiles and small mammals. CSP introduces higher risks, with bird collisions and solar flux burns. Wind turbines cause bird and bat fatalities, though mitigation such as blade painting reduces impacts, while offshore farms disrupt marine mammals and benthic ecosystems. Biomass cultivation reduces biodiversity through deforestation, monocultures, and pesticides. OTEC poses ecological risks through entrainment of plankton, larvae, and fish in seawater intakes, and habitat changes from deep-water pipes that may reduce biodiversity, though sometimes creating artificial reefs. Nutrient-rich discharges can trigger algal blooms, alter pH and carbon balance, and disrupt fisheries, coral reefs, and migration patterns. Ammonia leakage in closed systems can degrade aquatic habitats, as it's highly toxic to fish and other aquatic organisms.

Lifecycle and waste challenges also diverge. PV panels and batteries pose toxic and heavy metal risks at end of life. CSP relies on mirrors and salts that degrade and can become hazardous. Wind is comparatively favourable, with up to 80 percent recyclable materials, though blades remain problematic. Biomass depends heavily on supply chains, with imported feedstock raising emissions. OTEC faces marine-specific issues such as pipe corrosion and disposal of ammonia.

5.9.4 Conclusion environment impact

In conclusion, the environmental assessment shows clear differences between the five technologies. OTEC is the most land-efficient option and operates carbon-free. Even though closed-cycle systems pose risks of ammonia leakage with potentially serious ecosystem impacts, these are avoided in open-cycle designs. This system uses seawater and can also co-produce drinking water, a valuable benefit for Bonaire. While OTEC carries ecological risks such as nutrient-rich discharges, entrainment of marine life, and habitat disruption, these impacts can be mitigated through careful design, intermediate-depth discharges, intake screens, and site selection away from sensitive areas. In some cases, OTEC infrastructure may even create new marine habitats. Wind and PV stand out as the most balanced solutions, combining low emissions with manageable impacts on land, biodiversity, and waste. CSP provides valuable dispatchable capacity but comes with higher water demands and risks to bird life, making its deployment more sensitive. Biomass, by contrast, imposes the heaviest environmental burden, with high water use, direct emissions, biodiversity loss, and unsustainable land requirements, making it the least favourable option. For Bonaire, this ranking highlights the strategic value of combining compact PV, carefully sited wind, and OTEC as a long-term complement, while limiting reliance on biomass.

Chapter 6: Demand flexibility

This chapter aims to answer the second sub-question: **What *is the potential of demand-side flexibility in Bonaire's electricity system, based on consumer load patterns and willingness to adapt?***

The growing share of renewable energy in Bonaire's electricity system presents both opportunities and challenges. Ensuring a sustainable system stability, reliability, affordability, and flexible adaptation of the system to match available energy sources with variable demand. In this chapter, the potential for demand-side flexibility will be analysed. The analysis will begin with an overview of the current electricity demand, focusing on daily patterns to identify when flexibility is needed. This will be followed by an examination of the different customer categories, as defined by the utility company and network operator WEB Bonaire, along with their respective contributions to the island's total energy consumption. Next, the demand profiles and the potential for flexibility within each customer class will be assessed. The chapter will conclude with insights into the flexible capacity within Bonaire's energy system, which can be used in demand scenarios for modelling purposes and to help reduce the need for production and storage capacity.

6.1 Daily load patterns

As seen in Figure 12, the electricity demand of Bonaire is presented in megawatts for the period between 12 and 25 September 2024 (WEB internal data). Over this two-week span, the load profile shows a clear and repeating daily pattern, with demand rising and falling at a predictable rhythm. Despite some small variations caused by temperature changes, humidity, or cloudiness that influence the need for cooling, the general shape of the curve remains stable. The most notable feature of this cycle is the presence of two daily peaks, with the largest one occurring in the evening around 20:30–21:30, where demand reaches between 24 and 26.5 MW. A second, slightly smaller peak occurs in the afternoon between 15:00 and 16:00, typically ranging from 22 to 25.5 MW. At the other end of the cycle, the system reaches its lowest point in the early morning around 06:00, when demand falls to 17.5–19 MW, representing the base load of the islands electricity demand.

On Bonaire, demand is lowest overnight (00:00–06:00), when only essential loads remain active. A gradual rise occurs through the morning and midday, with a pronounced peak around 15:00–16:00 due to widespread air-conditioning demand as temperatures reach their maximum. After a slight dip when offices and businesses close, the highest load occurs in the evening between 20:30 and 21:30, driven primarily by residential cooling and household appliance use. Demand then declines steadily, returning toward the base load around midnight.

The exact height of the peaks varies from day to day, which can be explained by short-term changes in temperature and weather conditions. Hotter or sunnier days create stronger afternoon peaks as cooling demand intensifies, whereas cloudier or cooler days reduce air-conditioning use and flatten the curve. Tourism periods also play a role, as hotels, resorts, and restaurants add to demand, especially in the evenings. These drivers make the load profile sensitive to both social and climatic factors, but the general daily rhythm remains consistent.

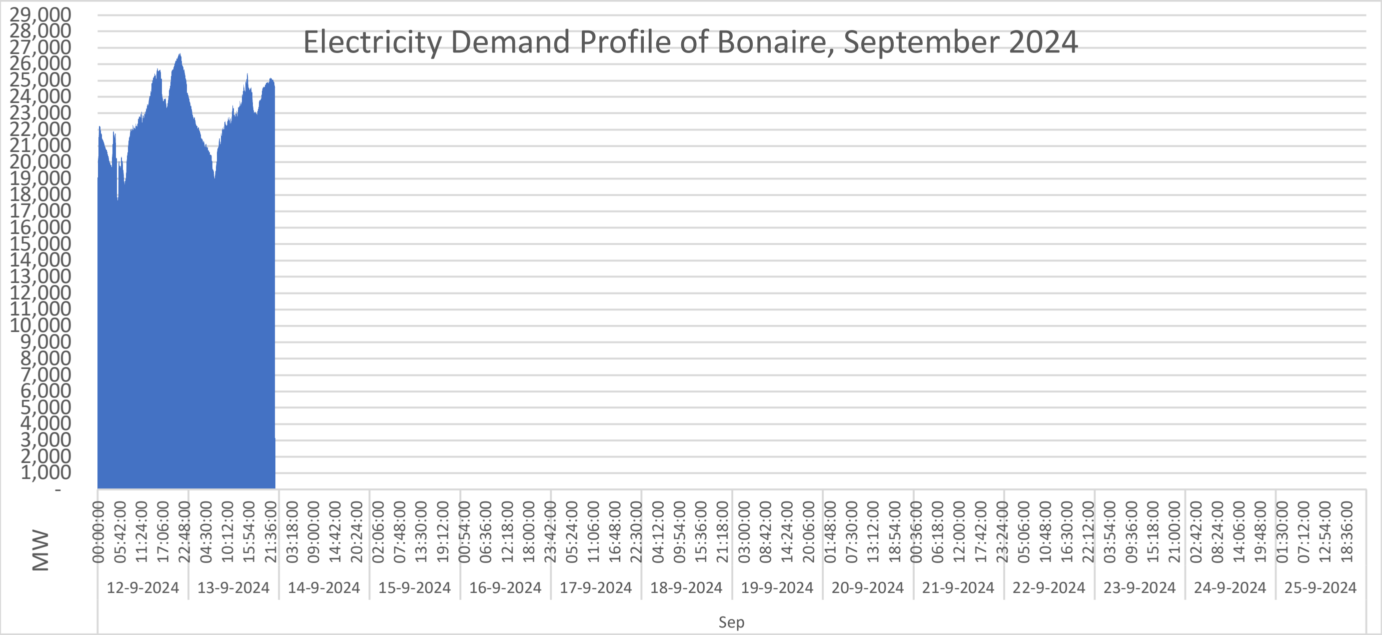


Figure 12: Daily load (MW) profile of Bonaire in September 2024, showing recurring peak electricity demand around 25–27 MW in the evenings, with lower daytime and early-morning loads around 18–20 MW (WEB internal data)

The difference between weekdays and weekends is not in the sequence of phases, which remains largely the same, but in the intensity of the peaks. On weekdays, both the afternoon and evening peaks are sharper and higher, reflecting the added influence of offices, schools, and commercial activity during working hours. On weekends, when many workplaces and schools are closed, the afternoon peak is flatter. People spending more time outdoors also reduces the need for air-conditioning during the day. The evening peak remains visible, but it is less pronounced compared to weekdays. Overall, weekdays are characterized by a stronger two-peak structure, while weekends show a smoother demand curve.

6.2 Flexibility needs and system implications

For system planning, these load dynamics have important implications. Bonaire experiences a swing of roughly 7–9 MW between the overnight valley and the evening peak. This is a significant variation for, which must ensure adequate generation capacity and reserve margins. Flexibility is therefore crucial, particularly during the two critical peak periods: the afternoon between 14:30 and 16:30 and the evening between 19:30 and 22:00. Shifting or reducing demand in these hours would ease system stress, reduce reliance on fossil fuel generation, and create space for more renewable energy integration. Conversely, the long off-peak window from roughly 22:00 until 14:30 the following day provides an opportunity to schedule flexible loads. Processes such as water desalination, electric vehicle charging, and other industrial or tourism-related operations can be shifted into these low-demand hours, flattening the load curve and making more efficient use of capacity. The observed 7–9 MW daily variation highlights the importance of demand flexibility. Strategies should aim to reduce or shift consumption during the afternoon and evening peaks while making better use of the extended overnight valley. By doing so, Bonaire can move toward a more stable and cost-efficient energy system, reducing overall system costs and enabling higher integration of renewable resources.

6.3 Demand customers

WEB Bonaire's customer service department provided data on electricity use by consumer class, including the number of connections, PV installations, and grid purchases. Table 3 summarizes these data for the main categories: commercial, hotels, industrial, small users (Kleinverbruik/KVB, neither residential nor large), public authority, and households. Commercial and residential users dominate electricity demand, together accounting for almost 80 percent of total consumption, making them the most important groups for understanding demand dynamics and flexibility potential. Hotels, industry, the water system, and KVB contribute only minor shares. Street lighting is reported separately but is excluded from flexibility analysis, as its demand is essentially constant at night and cannot be shifted.

Table 3: Electricity consumption by revenue class in Bonaire, according to WEB customer service data. Commercial and residential users account for nearly 80% of demand, followed by hotels, industry, and the water system. PV adoption remains limited, according to this inventory.

Revenue Class	**Connections**	**With PV system**	**Annual Consumption (GWh)**	**Share of Total (%)**
Commercial	1,872	25	55.26	39.5%
Households	8,267	185	54.15	38.7%
Hotel (all sizes)	11	1	9.76	7.0%
Industrial	47	0	6.65	4.7%
KVB (small non-res.)	316	6	2.40	1.7%
Other Public Authority	10	0	0.54	0.4%
Water System	—	0	10.51	7.5%
Street Lighting	—	0	0.80	0.6%
Total	10,523	217	140.1	100%

The dataset, however, shows limitations and inconsistencies. Reported solar generation by customers appears underestimated, likely because only net electricity purchased from the grid is captured on bills rather than total generation and self-consumption. Moreover, the classification of consumer categories is not applied consistently. For example, hotels and resorts are sometimes listed under commercial, industrial, and hotel classes simultaneously. The same applies to supermarkets, logistics companies, and utilities. Such overlaps blur the boundaries between categories, making it difficult to draw precise conclusions about sector-specific demand. Validation with WEB staff confirmed that consumer categorization is primarily designed for billing rather than energy demand studies. The billing system records only net purchases, without systematically linking to customer type, on-site solar PV production, or storage capacity.

Going forward, improvements in data collection and categorization are needed. As WEB's asset management department already uses GIS to map transformers and cables, there is an opportunity to integrate customer data into the same system. Combining smart metering, geographic information, and solar/storage tracking would enable much more accurate analysis of demand patterns, including time-of-day effects and sector-specific flexibility potential. This would also strengthen future planning for demand-side management and capacity expansion.

Given the data limitations for large consumers, this research focuses primarily on residential demand. Household energy use is more clearly defined, supported by more accurate data, and represents the largest and most reliable consumer class. Since households account for a significant share of total electricity demand, and their behavior is relatively homogeneous, they provide the strongest basis for assessing demand flexibility. By contrast, large consumers such as hospitality, industrial, and commercial users span multiple sectors with diverse and heterogeneous consumption patterns, while reliable sector-specific data are limited. These constraints make detailed modelling of large customers less robust, so they are considered separately but not as the focus of the flexibility analysis. The water system is also reviewed. KVB users are excluded due to uncertainty in classification, public authority consumers are grouped with large users, and street lighting is excluded since its constant nighttime profile offers no potential for flexibility.

6.4 Households demand flexibility

Bonaire's population growth is a critical driver of future electricity demand. As seen in figure 13, the 2023 forecast, the population was expected to grow from about 25,100 in 2024 to 28,600 in 2030, corresponding to an average annual increase of around 2.2% per year. However, the latest CBS forecast (2024) revised this outlook upward. The population is now projected to rise from 25,100 in 2024 to just over 34,000 by 2035, which equals an average annual growth rate of about 2.7% per year. This acceleration is largely the result of higher-than-anticipated migration. The stronger demographic growth means that households will remain a major and increasingly important driver of electricity demand, reinforcing their relevance as a target group for demand flexibility strategies.

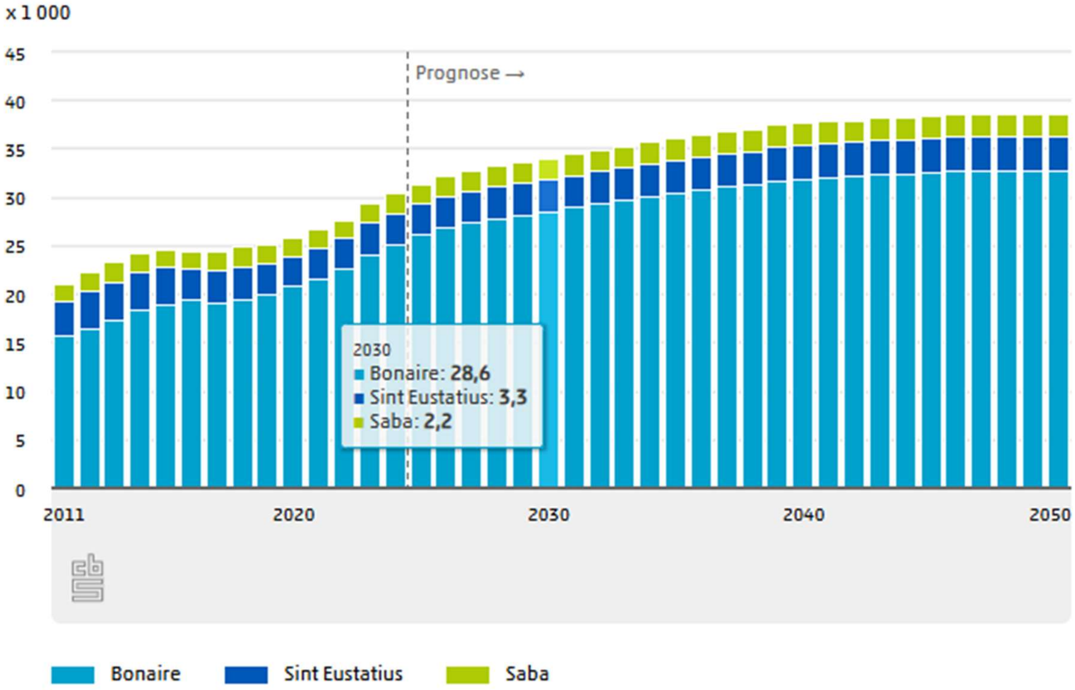


Figure 13: Population growth projection for Bonaire, showing steady increase from around 19,000 in 2011 to about 28,600 in 2030, with further growth expected through 2050. (Centraal Bureau voor de Statistiek, 2020)

6.4.1 Households demand pattern

Figure 14 shows the measured load profile of a neighbourhood with 64 households between 14 and 22 September 2024 (WEB internal data). The values represent real power (kW), summed over three phases. A distinct daily cycle is visible, with demand ranging between about 80–100 kW at night (roughly 1.2–1.6 kW per household) and 180–200 kW during peak times (about 2.8–3.1 kW per household).

When compared to the island-wide load curve, the neighborhood profile follows the same overall daily rhythm but with distinct differences. In the afternoon (15:00–16:00), neighborhood demand remains relatively low because many residents are away from home, while at the island level this period shows a pronounced peak driven by commercial, industrial and office loads. In the evening (19:30–21:30), both curves show their maximum, as households return home and electricity use increases. On weekends, the neighborhood profile develops a more visible double peak, with higher afternoon demand in addition to the evening maximum, reflecting greater time spent at home. By contrast, the island-wide weekend curve flattens, as commercial and institutional loads fall away.

Taking together, these profiles highlight two key points. First, afternoon peaks at the island level are mainly driven by commercial and public-sector cooling rather than households. Second, evening demand is primarily residential, creating the dominant daily peak. This distinction is crucial for planning flexibility measures: household-oriented options such as appliance shifting and EV charging are best targeted at evening demand, while commercial demand-side programs would be most effective in addressing the afternoon peak.

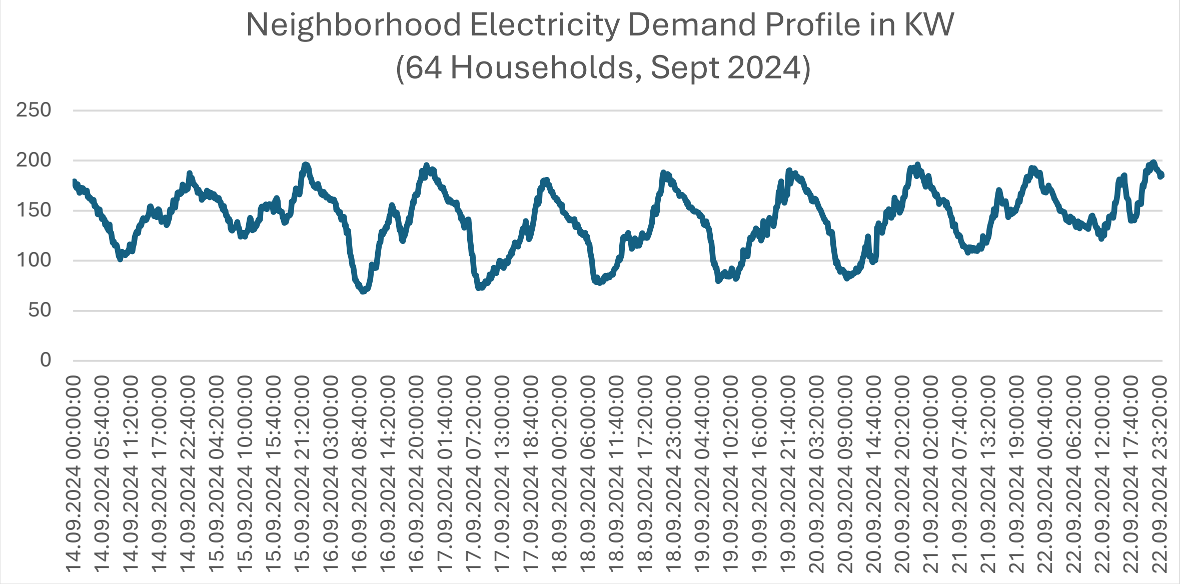


Figure 14: Neighbourhood electricity demand profile for 64 households in Bonaire (September 2024), showing daily load fluctuations between ~80 kW at night and ~200 kW during peak evening hours, with a consistent diurnal cycle across the week (WEB internal data)

6.4.2 Households demand flexibility strategies

As discussed in Section 2.2.2, Demand-Side Management (DSM) refers to long-term measures that permanently reduce electricity use through efficiency and conservation. By lowering baseline demand, DSM reduces dependence on non-renewable supply and eases congestion on the network. Programs typically begin with awareness and information, for example through bill feedback, and are supported by incentives such as rebates, subsidies, point-of-sale discounts, or on-bill financing to overcome investment barriers. Practical household actions include switching off unnecessary loads and adopting efficient appliances and lighting. Replacing incandescent bulbs with LEDs, upgrading refrigerators and air conditioners, and using ceiling or standing fans in place of, or alongside, air conditioning can significantly reduce consumption during peak hours. Building-related improvements such as insulation, air sealing, shading, films, and reflective roofs further decrease cooling demand.

Demand Response (DR) delivers short-term, flexible adjustments in response to Time-of-Use, dynamic, or critical-peak prices. The evening peak around 19:30–21:30 is mainly residential, household flexibility is most effective in the evening, whereas commercial DR should target the afternoon. DR incentives should encourage households to shift usage away from these peak windows and toward off-peak hours. The primary off-peak window extends from 22:00 to 14:00, during which activities such as laundry, dishwashing, tumble drying, pool pumping, and EV charging should be concentrated. A limited secondary window from 17:00 to 19:00 can also be used for pre-cooling and cooking, though it should remain modest since it sits close to the evening peak and is best combined with self-supply.

If DSM has already achieved maximum reductions and DR has shifted demand as far as possible, a third option is to rely on distributed self-supply. Home storage, vehicle-to-grid capable EVs, and rooftop solar PV can provide electricity during peaks, with EV batteries discharging back into the home or grid at critical times. This is especially valuable for uses that cannot be shifted, such as night-time air conditioning or outdoor lighting. Charging EVs and home batteries at night or midday and discharging between 19:30 and 21:30 not only relieves grid stress but also improves energy independence. With the right incentives, self-supply becomes financially attractive by taking advantage of higher peak tariffs.

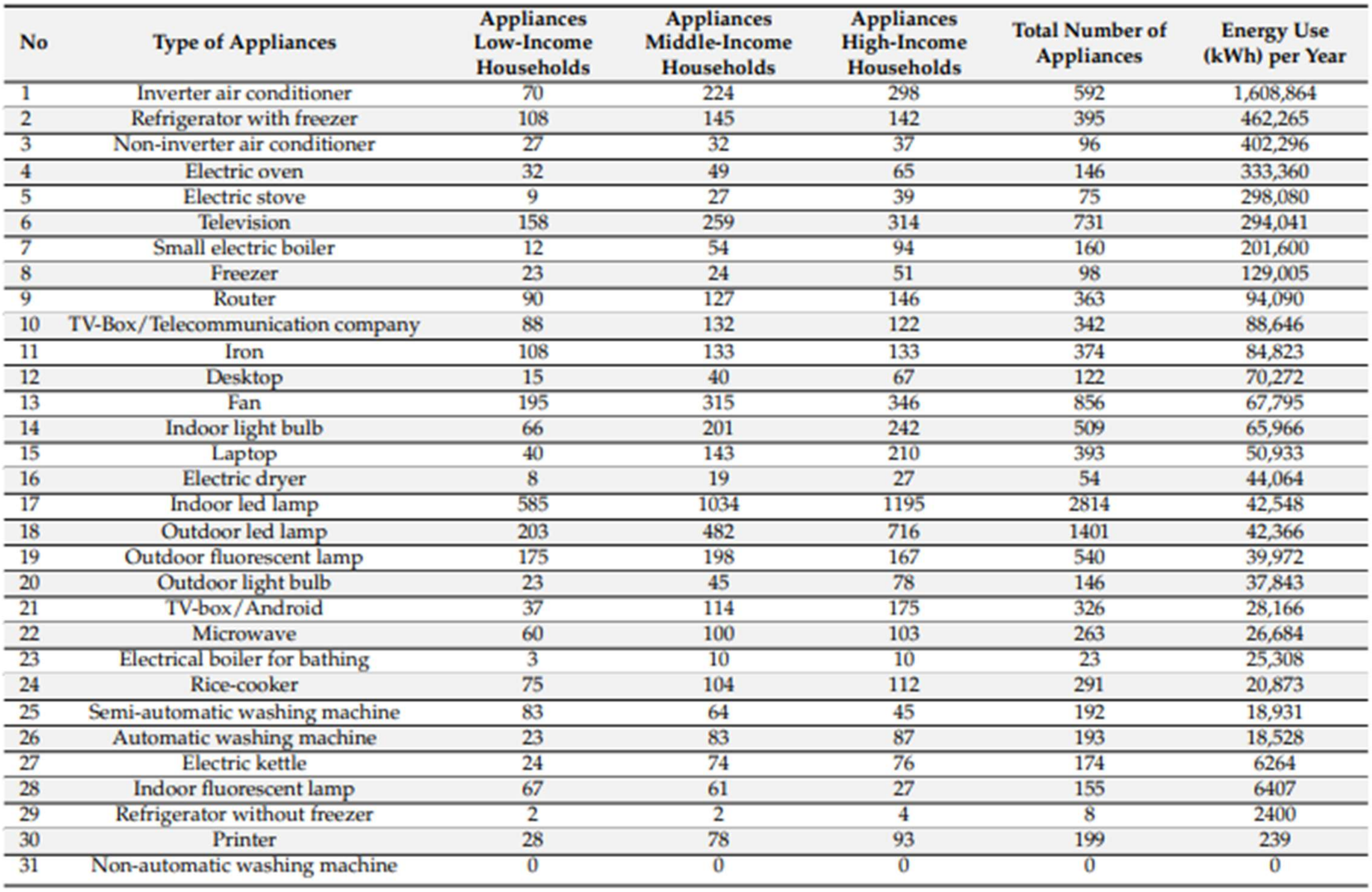
Together, DSM reduces overall demand over time while DR reshapes its hourly distribution. These strategies guide Bonaire toward a more stable, cost-efficient, and cleaner power system, consistent with Sections 2.2.2 and the Short-Duration Flexibility Ladder. The ladder emphasizes low-cost, easy-to-adopt household measures such as smart thermostats and appliance scheduling, which are highly effective in reducing or shifting use during peaks. Improvements in insulation and pre-cooling further reduce reliance on air conditioning in Bonaire's hot climate. Over the longer term, EV batteries and home storage will play an increasingly important role, charging at night or midday and supplying energy during the evening peak, particularly as rooftop solar adoption grows.

6.4.3 Bonaire appliance penetration and flexibility options

To approximate appliance penetration and end-use contributions in Bonaire, this analysis references a recent household energy study from Curaçao (telephone survey of 382 households) that reports appliance ownership and total annual energy by device type(Bulbaai & Halman, 2024) (Table 4). Given the islands' similar climate and cooling needs, the table provides a reasonable proxy for the appliance mix shaping residential demand on Bonaire. The Curaçao results indicate that air conditioning is the dominant end use, followed by refrigeration and electric cooking/small electric boilers; lighting is high in unit count but low in per-unit consumption; and routers/TV boxes contribute a persistent 24/7 baseload. These patterns support DSM priorities, efficient/variable-speed ACs, refrigerator upgrades, and building-envelope measures, and DR actions such as pre-cooling with evening setbacks, scheduling laundry/dishwashers, and avoiding electric cooking during peaks. Table 5 assesses the potential of the Demand side flexibility strategies on different appliances and the potential peak impact.

Table 6 shows how DSM and DR strategies can incentivize on-site generation and storage, rewarding self-consumption during peak periods while reducing system demand. Applied effectively, these measures shift flexible loads to hours of high PV output and use on-site resources to cover the evening peak around 19:30–21:30, thereby lowering grid demand and overall system costs.

Table 4: Household appliance ownership and associated annual energy consumption across income groups, based on a Curaçao study of 382 households. The results show that high-income households have greater adoption of energy-efficient appliances; while cooling and refrigeration dominate overall household energy use. (Bulbaai & Halman, 2024)



No	Type of Appliances	Appliances Low-Income Households	Appliances Middle-Income Households	Appliances High-Income Households	Total Number of Appliances	Energy Use (kWh) per Year
1	Inverter air conditioner	70	224	298	592	1,608,864
2	Refrigerator with freezer	108	145	142	395	462,265
3	Non-inverter air conditioner	27	32	37	96	402,296
4	Electric oven	32	49	65	146	333,360
5	Electric stove	9	27	39	75	298,080
6	Television	158	259	314	731	294,041
7	Small electric boiler	12	54	94	160	201,600
8	Freezer	23	24	51	98	129,005
9	Router	90	127	146	363	94,090
10	TV-Box/Telecommunication company	88	132	122	342	88,646
11	Iron	108	133	133	374	84,823
12	Desktop	15	40	67	122	70,272
13	Fan	195	315	346	856	67,795
14	Indoor light bulb	66	201	242	509	65,966
15	Laptop	40	143	210	393	50,933
16	Electric dryer	8	19	27	54	44,064
17	Indoor led lamp	585	1034	1195	2814	42,548
18	Outdoor led lamp	203	482	716	1401	42,366
19	Outdoor fluorescent lamp	175	198	167	540	39,972
20	Outdoor light bulb	23	45	78	146	37,843
21	TV-box/Android	37	114	175	326	28,166
22	Microwave	60	100	103	263	26,684
23	Electrical boiler for bathing	3	10	10	23	25,308
24	Rice-cooker	75	104	112	291	20,873
25	Semi-automatic washing machine	83	64	45	192	18,931
26	Automatic washing machine	23	83	87	193	18,528
27	Electric kettle	24	74	76	174	6264
28	Indoor fluorescent lamp	67	61	27	155	6407
29	Refrigerator without freezer	2	2	4	8	2400
30	Printer	28	78	93	199	239
31	Non-automatic washing machine	0	0	0	0	0

Table 5: Assessment of demand-side flexibility strategies for household appliances, outlining typical peak-use behaviour, potential DSM/DR measures, and the estimated peak demand reduction per household. Results highlight significant flexibility potential in air conditioning, water heating, washing machine, dishwasher and tumble dryers, while refrigeration, ICT devices, and lighting offer only marginal peak impact reductions (Own elaboration using :Power Consumption of Typical Household Appliances, n.d.).

Category	**Demand Flexibility potential (DSM/DR)**	**Peak impact (kW) estimation**
Air conditioning	DSM+DR: efficient AC, Pre-cool 17:00–19:00, then set-back 19:30–21:30; resume after. Raise setpoint slightly and use fans to coast through the peak.	0.75–3
Refrigeration (fridge/freezer)	DSM: Not shiftable; upgrade to efficient/inverter units	X
Cooking & kitchen appliances *(stove/oven, microwave, rice cooker, kettle/boiler, blender, toaster, air fryer)*	DSM + limited DR: prefer induction/fast cookers. Cooking time is set.	0.5–3
Electronics & entertainment *(TVs, laptops/desktops, consoles, speakers)*	DSM+DR: Use power-save; schedule charging around 22:00 – 14:00;	0.1–0.3
ICT always-on *(router / TV-box / smart hub)*	Limited DSM: Choose efficient models; enable eco modes;	X
Electric water heater / boiler	DR limited + DSM: lower setpoint; insulate tank/pipes.	4–14
Fans	DSM+DR: Use with/instead of AC to allow a higher setpoint while maintaining comfort at peaks.	0.2–0.4
Tumble dryer	DR+DSM: use during 22:00–14:00 or use with own PV system generation; line-dry when possible.	1–4
Lighting (indoor & outdoor)	DSM: Not shiftable; switch to LEDs; use dimmers/occupancy or motion sensors; minimize non-essential use in peaks.	x
Washing machine	DR: use during 22:00–14:00 or use with own PV system generation	0.5–1.0
Dishwasher	DR +DSM: use during 22:00–14:00 or use with own PV system generation; use Eco program, skip heated-dry.	1.2–1.5
Household goods *(vacuum, iron)*	DR+DSM: Vacuum/iron 22:00 –14:00	0.4–2.5
Bathroom devices *(hair dryer, shaver, straightener)*	DR: Use off-peak where feasible (mornings/weekends).	0.1–0.5
Swimming pool (pump/filter)	DR: use during 22:00–14:00 or use with own PV system generation	0.2–1.5

Table 6: Flexibility options for distributed energy resources in households, showing how solar PV, home batteries, and electric vehicles (EVs with smart charging or V2G) can provide demand-side management (DSM) and demand response (DR). While solar PV mainly reduces daytime demand through self-consumption, batteries and EVs offer significant evening peak-shaving potential (own elaboration).

Category	**Flexibility Options & Grid Impact**
Solar PV	DSM incentives (e.g., subsidies, tax rebates) can expand rooftop PV adoption, cutting central demand through self-consumption. Demand response programs align flexible loads such as washing machines or water heating with midday PV output, ensuring local use of surplus generation. If excess remains, exports can be compensated. Together, this reduces daytime grid demand, limits midday oversupply, and eases stress on central generation.
Home Battery	Incentives for household batteries lower grid dependency and maximize the value of rooftop PV. Batteries are charged during midday PV surplus or off-peak hours and discharged during evening peaks (19:30–21:30). This directly reduces fossil generation at critical times, flattens the load curve, and enhances local supply security.
EV (Smart Charging & V2G)	Smart charging shifts demand to off-peak hours (22:00–14:00) or PV surplus periods, avoiding simultaneous charging during evening peaks. With vehicle-to-grid (V2G), EVs can discharge back into the grid between 19:30–21:30 while maintaining a minimum state of charge for mobility. This transforms EVs into mobile storage, reduces peak load, and strengthens grid flexibility.

6.4.4 Validation of household's willingness of demand-side flexibility in Bonaire

WEB Bonaire has already tested elements of demand flexibility, as seen in appendix D. During the August 2023 heatwave, record air-conditioning demand combined with unusually low wind output created a supply–demand imbalance. To prevent outages, WEB and ContourGlobal issued an island-wide appeal urging residents to turn off unnecessary lights, unplug idle electronics, switch to LED bulbs, and set air conditioners to 23 °C (WEB & CGB, 2023b). Although temporary, this intervention demonstrated how short-term demand response (DR) and long-term demand-side management (DSM) can complement one another to relieve grid stress and enhance resilience.

The effectiveness of such information campaigns at the household level remains uncertain, however, which is why willingness and adoption were explicitly included in WEB's 2025 customer satisfaction survey. This survey, with 791 household responses (see Appendix E1), provides a representative view of demand flexibility across Bonaire. About 15% of respondents report that they have rooftop solar panels, though only 5% use a home battery, and just 2% of all households own an EV. These low adoption levels highlight significant potential for growth in distributed resources. Yet without structured DR, self-generation and storage alone will not effectively reduce evening peaks.

Energy-saving measures are already common but uneven. Roughly 52% of households reported at least one measure in 2025, down from 2022/23. LEDs and inverter air-conditioners are most widespread, while presence sensors, insulation, and shading remain limited. This points to opportunities to refresh DSM campaigns to focus on adoption of energy-saving technologies.

Survey responses also show strong willingness to participate in DR. About 42% of households would shift voluntarily, while another 24% would do so when explicitly asked. This provides a clear basis for introducing ToU pricing or peak-event alerts structured around Bonaire's operating windows. Loads should be shifted away from 14:30–16:30 and 19:30–21:30 and steered into 22:00–14:00, with 17:00–19:00 used only for limited pre-cooling, cooking, or other priority tasks. Where evening operation is unavoidable, it should rely on self-supply from PV, batteries, or EVs. The most suitable targets for DR programs include air conditioning (pre-cool/set-back), tumble dryers, dishwashers, washing machines, pool pumps, EV charging, and storage-type electric water heaters.

6.4.5 Conclusion: Residential demand-side flexibility

The 2025 household survey confirms a strong basis for demand flexibility on Bonaire. About 42 percent of households indicated they would shift electricity use voluntarily, while another 26 percent would do so if they were prompted. Some DSM measures are already in place, with LEDs and inverter air conditioners most common, but shading, insulation, and sensor-based controls remain less developed. This suggests that households are both willing and able to adapt, yet much of the DSM potential is still untapped. More targeted information and awareness campaigns could therefore accelerate the adoption of efficiency and conservation measures.

Demand response is not yet implemented in practice, but the survey results indicate that it could play a major role in enhancing demand-side flexibility. Shifting appliances such as washing machines, dishwashers, pool pumps and electric vehicle charging away from peak hours between 14:30 and 16:30 and between 19:30 and 21:30 toward off-peak times, particularly midday when solar PV is abundant, would directly align household behaviour with system needs. Air conditioning, the main driver of the evening peak, offers scope for demand response through pre-cooling, modest set-point adjustments and the use of fans alongside efficient inverter units. Self-supply complements both efficiency improvements and demand response, as rooftop PV can meet daytime demand while batteries and electric vehicles can store surplus generation for evening use.

Together, these findings show that households are already engaged in some efficiency improvements and willing to shift their demand when prompted. Expanding DSM through stronger information campaigns and introducing DR programs would unlock much greater flexibility, lowering household bills, reducing grid stress, and supporting Bonaire's transition to a renewable and resilient power system.

6.5 Large Consumers demand flexibility

Bonaire's load shows two distinct peaks with different drivers: the afternoon peak (14:30–16:30) is largely associated with commercial, industrial, and public-sector activity, while the evening peak (19:30–21:30) is predominantly residential as people return home. In this section, the potential for demand-side flexibility among large consumers is briefly assessed and validated through the survey results. A more detailed analysis of large consumer categories, their energy use, and their flexibility potential is presented in Appendix F.

For large commercial, industrial, and hospitality users the need for self-generation is more pronounced because shifting is constrained by operating hours and quality of service. Offices and public facilities run primarily in the daytime, so many loads coincide with the afternoon peak. Hotels and hospitals must maintain cooling, lighting, hot water, kitchens, laundry, and specialized equipment whenever guests or patients require them, which limits evening flexibility. Pairing DSM and DR with on-site PV, batteries, and, where available, vehicle-to-grid fleets allows these time-locked loads to be met without increasing net grid draw during peaks, thereby reducing exposure to peak tariffs and demand charges. The economy is generally stronger at large sites. Scale provides lower unit costs for PV, batteries, and larger roofs and car parks raise the share of PV consumed on-site.

6.5.1 Validation of large consumers' willingness for demand flexibility in Bonaire

WEB contacted 136 large customers; 38 completed the questionnaire (28% response), see appendix E2. Respondents span all major sectors: industry, electricity/cold production and distribution, construction, wholesale/retail, transport and storage; hospitality, real estate, finance, education, health and social care and other services. providing a broad view of commercial and industrial activity on Bonaire.

On-site generation and storage are becoming increasingly common in Bonaire. Survey results show that a significant share of consumers already operate back-up generators or solar PV systems, with uptake having grown steadily since 2020. Businesses report higher adoption rates than households, reflecting both the bill savings already achieved through demand-side measures and the favourable investment case for on-site generation. While formal demand response instruments are not yet in place, their introduction would further enhance the economics and flexibility potential of storage and self-generation by rewarding supply during high-cost evening hours and enabling price arbitrage. This is likely to accelerate investment in batteries and, where relevant, vehicle-to-grid (V2G) fleets.

Efficiency adoption on Bonaire is high but not yet complete: 89% of respondents report having implemented at least one measure. The most common are energy-efficient cooling (27%), LED lighting (22%), and presence-sensing light controls (19%), while fewer households report roof, wall, or window insulation (6%) or other measures (1%).

6.5.2 Conclusion: large customers demand-side flexibility

The same reduce → shift → self-supply sequence used for households applies to large sites. Demand Side Management strategies, such as information campaigns and economic incentives are needed to further encourage and accelerate the adoption of efficiency measures.

The extent of electricity reduction differs by sector depending on energy uses, underscoring the importance of continued investment in higher efficiency measures. The survey results confirm both the willingness and partial adoption of such measures. suggesting that broader deployment, supported by demand-side management incentives, could strengthen flexibility potential and lower energy bills.

A unified off-peak schedule (22:00–14:00) can be applied across major end uses. HVAC can be pre-conditioned during this period, pre-cooled before the evening peak (17:00–19:00), set back through 19:30–21:30, and return to normal after 22:00. Other loads such as laundry, pumps, blowers, motors, water heating, and tools can also be shifted mainly into 22:00–14:00, with staging to avoid coincident starts. Storage-based water heaters should heat during this window, while tankless units should be reserved for off-peak use. In construction, automotive, and logistics, compressors and tools should also operate off-peak, avoiding overlap that could increase demand.

While demand-side measures help reduce and shift consumption, the largest remaining potential to relieve Bonaire's afternoon (14:30–16:30) and evening (19:30–21:30) peaks lies in on-site generation and storage for self-supply. Daytime processes can be aligned with solar PV to raise self-consumption and reduce midday imports, while batteries and vehicle-to-grid (V2G) fleets can be charged during off-peak hours (22:00–14:00) and discharged during the evening peak to cover non-shiftable cooling, lighting, ICT, and process loads without increasing grid demand. This 'shift-or-self-supply' approach is particularly effective for large customers, whose operating hours and service requirements limit flexibility but whose economies of scale, centralized control, and lower unit costs strengthen the investment case.

6.6 Drinking water plant

Water- en Energiebedrijf Bonaire (WEB) is not only the island's electricity network operator and retailer but also operates Bonaire's drinking water production facility. The plant supplies the entire island by desalinating seawater through reverse osmosis, an energy-intensive process that accounts for about 7.5% of Bonaire's total electricity consumption.

Efficiency improvements are possible in both the desalination process and the associated pumping systems. The newer WEB2 trains achieve a specific electricity use of 2.98 kWh per m^3, compared to 3.40 kWh per m^3 for WEB1 and 3.12 kWh per m^3 for the temporary plant (WEB internal data). This means WEB2 is approximately 12% more efficient than WEB1 and 5% more efficient than the temporary facility. Auxiliary systems also contribute significantly to energy use. Seawater lift and intake pumping require 0.60 kWh per m^3, which is more than twice the 0.29 kWh per m^3 used by distribution pumps. This indicates that optimizing seawater pumps has a larger effect on overall electricity consumption than focusing on distribution pumps. These efficiency gains have a substantial impact on the island's total energy use and could help reduce peak demand on the grid, especially since water production aligns with household electricity consumption in the evening hours.

The water production record shows that daily output typically ranges between 7,000 and 8,000 m^3, with occasional peaks up to 9,500 m^3 and drops as low as 2,000–4,000 m^3 (WEB internal data). This demonstrates that the plant already operates flexibly on a daily basis, with headroom to ramp production up or down as required. This flexibility suggests good potential for Demand Response, where production is shifted to align with renewable availability and system conditions. In practice, output should concentrate during the off-peak period (22:00–14:00), with storage tanks filled ahead of the afternoon and evening peaks so that the high-pressure trains can idle or run at minimum during 14:30–16:30 and 19:30–21:30. However, while the production record confirms variability on a daily scale, effective demand response requires flexibility on an hourly basis. Therefore, any schedule must be validated against both storage capacity and firm production capability to ensure that tanks can cover peak windows and be replenished in subsequent off-peak hours.

6.6.1 Operational validation with the water-plant manager

To validate the demand-flexibility assessment, a meeting was held with the operational manager of the drinking-water plant. He explained that the facility operates nine reverse-osmosis trains continuously to keep treated-water storage between 80 and 90 percent. The plant's combined electrical demand is about 1.3 MW, roughly five percent of the island's peak demand of 26 MW, large enough to be relevant for peak management. In practice, however, the scope for routine curtailment is limited. Reducing capacity requires shutting down one or more RO trains, and restarting introduces pressure transients that shorten membrane life. Because membrane replacement is costly, frequent start–stop cycling is avoided. Curtailment also lowers storage levels and then requires long recovery periods. While expanding storage and adding new production capacity are planned to accommodate population and tourism growth, very large storage volumes bring challenges of their own: longer residence times increase the risk of bacterial regrowth, and water quality requires regular turnover.

Some emergency flexibility is available. At the request of the electricity department last year, the plant reduced load by about 0.5 MW for six hours, after which recovery was manageable. According to the manager, this level of curtailment could be offered two to three times per year under exceptional conditions, but not as a daily evening practice. Frequent shutdowns would damage membranes and significantly raise operating costs.

6.7 Mobility sector: emerging flexible demand

As shown in the previous analysis, electrification of mobility is present in both households and large customers, and it will be a major new source of flexible demand and should be a priority for Demand Side Management and Demand Response. By 2030 the fleet expands sharply as seen in table 7. Two- and three-wheelers and other light electric vehicles grow by approximately threefold, cars by approximately eightfold, and light commercial vehicles by fivefold, with the first electric trucks and buses entering service. This scale of growth gives the mobility sector substantial technical potential for managed flexibility through smart charging and, where feasible, vehicle-to-grid operation.

Table 7: Projected growth of electric vehicles (EVs) in Bonaire across different categories (2024–2040). Two/three-wheelers and light electric vehicles (LEVs) dominate early adoption, reaching 100% penetration by 2040. Cars grow steadily to 37% of the fleet, while buses and trucks expand more gradually but show significant shares by 2040 (56% and 9%, respectively). Average charging power requirements vary by vehicle type, from 2 kW for 2/3-wheelers to 50 kW for buses and trucks (WEB internal forecasts).

Vehicle category	**Avg. charging power (kW)**	**2024 (# EV / % of total)**	**2030 (# EV / % of total)**	**2035 (# EV / % of total)**	**2040 (# EV / % of total)**
2/3-wheelers & LEV	2 kW	750 / 21%	2,250 / 56%	3,500 / 78%	5,000 / 100%
Cars	5 kW	200 / 1%	1,647 / 7%	3,176 / 12%	11,100 / 37%
Light commercial vehicles	11 kW	22 / 1%	104 / 4%	190 / 7%	381 / 12%
Trucks (overnight)	50 kW	– / 0%	1 / 1%	9 / 4%	26 / 9%
Buses	50 kW	– / 0%	6 / 17%	16 / 40%	25 / 56%

In 2030 the potential peak impact of unmanaged electric-vehicle charging is large and is dominated by cars. If every vehicle charged at its average rate at the same time, the instantaneous load would be about 14.2 MW. Because most drivers return home in the evening and tend to plug in on arrival, charging would cluster between 19:30 and 21:30 and push the system upward, even if only a modest share of vehicles charged simultaneously.

The management approach for mobility should follow the same framework used elsewhere in this report. Demand Side Management and Demand Response should schedule default charging in the 22:00 to 14:00 window, with priority from 11:00 to 14:00 so vehicles absorb midday solar photovoltaic output. Charging should be locked out between 19:30 and 21:30 to protect the evening peak. Where Vehicle-to-Grid capability is available, controlled discharge should be enabled from 19:30 to 21:30 while preserving a minimum state of charge for the next day's travel. Demand Side Management should also provide incentives in smart charging hardware and time-varying tariffs and peak-event programs that reward off-peak charging and evening Vehicle-to-Grid support. Managed in this way, transport electrification in 2030 becomes a controllable two-way resource that shifts demand into off-peak and solar hours while holding the evening peak flat.

6.8 Conclusion demand flexibility

This chapter examined how Bonaire can align a growing share of renewable generation with a more flexible pattern of electricity use. The system goals of stability, reliability, affordability and sustainability were translated into practical operating rules: avoid the afternoon peak between 14:30 and 16:30, avoid the evening peak between 19:30 and 21:30, concentrate demand in the off-peak window from 22:00 to 14:00, and allow limited pre-cooling between 17:00 and 19:00.

The assessment shows that Bonaire has significant opportunities to reduce peak demand and integrate renewable electricity through efficiency improvements, demand response and self-supply. Household surveys indicate a strong willingness to shift flexible loads, while large customers already apply some efficiency measures and express strong interest in on-site generation and storage. The water system, although a large single load, provides only limited flexibility: steady reverse-osmosis operation and careful scheduling can support the grid, but daily cycling is not feasible. The mobility sector presents both a risk and an opportunity. Unmanaged electric-vehicle charging could add several megawatts to the evening peak by 2030, yet managed charging and vehicle-to-grid could instead provide valuable flexibility.

Across all sectors, rooftop solar and batteries create an important pathway for self-supply, especially when combined with tariffs that reward midday consumption and evening discharge. WEB Bonaire will play a central role in guiding this transition through tariff design, awareness programs, standard contracts, streamlined permitting and targeted support for efficient equipment and distributed generation.

Overall, Bonaire combines technical potential with consumer readiness to support higher shares of renewable energy. A phased roll-out of demand-side measures supported by dynamic pricing, peak-event notifications, default energy-management schedules and managed charging can flatten the evening peak while maintaining service quality. In doing so, Bonaire can improve system reliability and affordability and strengthen its energy security on the path toward a fully renewable electricity system.

Chapter 7: Storage Flexibility

This chapter aims to answer the third sub-question: ***What energy storage solutions are suitable for Bonaire's electricity system, considering centralized and decentralized applications as well as the required storage duration and capacity?***

The chapter discusses the role of storage in integrating renewables, outlines the range of available technologies, assesses their feasibility in Bonaire's context, and examines the trade-offs between centralized and decentralized applications to identify the most suitable options for a secure and sustainable energy system.

7.1 Storage technologies and their role in renewable integration

Flexibility of storage is illustrated in Figure 15 (U.S. Grid Energy Storage Factsheet, n.d.). During low-demand periods, such as at night or midday when solar production is high, storage absorbs surplus electricity that would otherwise be curtailed. This stored energy is then released during high-demand periods, particularly in the evening peak, to cover the gap between renewable generation and consumption. By shifting energy from periods of excess to periods of scarcity, storage helps smooth the variability of solar and wind, supports continuous power supply, and reduces dependence on expensive and polluting diesel generators (Li & Deusen, 2025). The ability to align supply and demand in this way makes storage a cornerstone of a high-renewable power system for Bonaire.

On Bonaire, a central lithium-ion Battery Energy Storage System (BESS) is already operational, providing short-term load shifting, such as storing excess solar generation for evening peaks, alongside frequency and voltage regulation to improve power quality, and emergency backup during outages or generation gaps. In small island grids, BESS is particularly effective due to its rapid response, scalability, and multi-functionality (Misic et al., 2025).

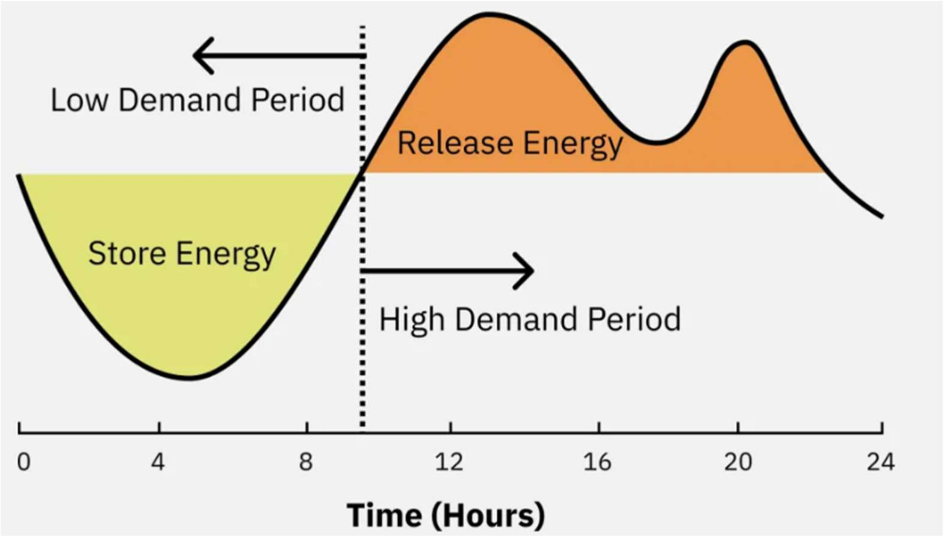


Figure 15: Flexibility of storage (U.S. Grid Energy Storage Factsheet, n.d.)

Besides shifting renewable generation across time, storage can also serve different functions for grid stability, bridging power, and energy management. Figure 16 illustrates the range of storage technologies by their discharge duration and power rating, showing how different solutions fit distinct system needs (U.S. Grid Energy Storage Factsheet, n.d.) (Li & Deusen, 2025).

- **Power quality**: As shown on the left side of the figure, short-duration storage such as high-power supercapacitors, superconducting magnetic energy storage, and flywheels operate in the seconds-to-minutes range. These technologies absorb or inject power rapidly, ensuring voltage and frequency stability and smoothing fluctuations on the grid.
- **Bridging power**: The middle section of the figure highlights medium-duration storage like lithium-ion, nickel-based, lead-acid, and flow batteries. These systems provide backup for minutes to hours, helping stabilize transmission and distribution networks and covering short gaps between supply and demand.
- **Energy management**: On the right side of the figure, long-duration technologies such as pumped hydro storage, compressed air energy storage, sodium-sulfur batteries, and hydrogen with fuel cells operate for hours to days. These solutions enable bulk energy shifting from low-demand to high-demand periods, supporting long-term reliability and reducing reliance on fossil fuels.

Together, the figure demonstrates that storage is not a single technology but a portfolio of solutions, each suited to a different role in delivering flexibility for a renewable-based energy system. For Bonaire to achieve a 100% renewable energy future, a combination of complementary solutions will be required, since diesel generators can no longer be relied upon for stability and backup. Solar PV and wind will remain the backbone of renewable generation, but both are variable and cannot fully match demand on their own. To ensure stability, reliability, and affordability, storage technologies must play a central role.

Short-duration storage (such as batteries and flywheels) will provide the fast response needed to maintain grid frequency and voltage. Medium-duration storage (including lithium-ion and flow batteries) will help bridge evening peaks and short gaps in renewable generation. Long-duration storage solutions will be essential for covering extended periods of low wind or solar, ensuring supply security without diesel backup.

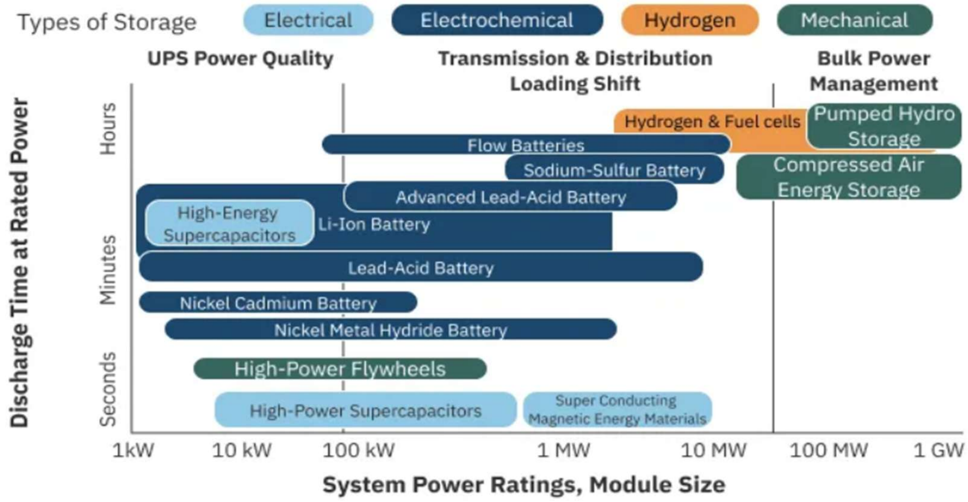


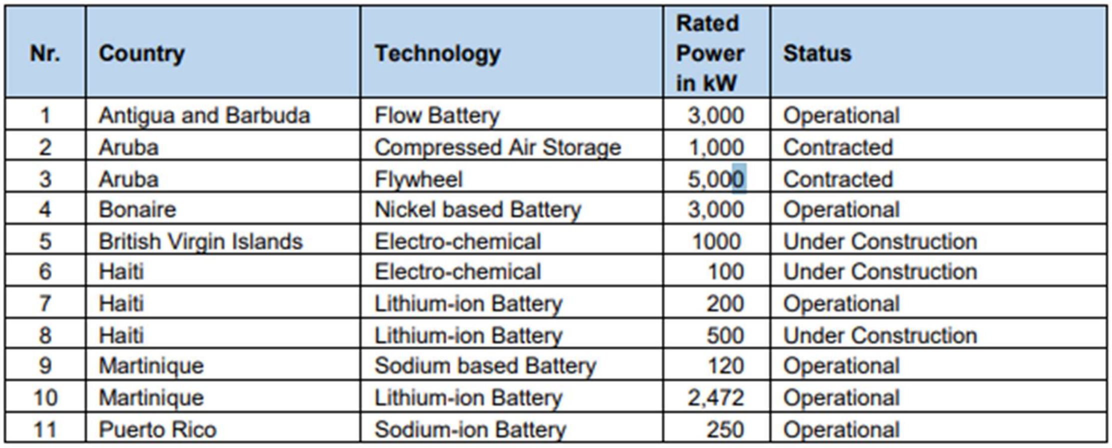
Figure 16: Range of energy storage technologies categorized by discharge duration and system power rating. Short-duration storage (supercapacitors, flywheels) supports power quality, medium-duration storage (batteries, flow cells) provides bridging power, and long-duration storage (pumped hydro, compressed air, hydrogen) enables bulk energy management for reliable integration of renewables (U.S. Grid Energy Storage Factsheet, n.d.)

7.2 Storage feasibility for Bonaire

Most storage technologies do not depend on geographical conditions and can be installed almost anywhere, making them technically feasible for Bonaire. However, some options such as Pumped Storage Hydropower (PSH) and Compressed Air Energy Storage (CAES), are highly site-specific and not suitable for the island. PSH requires two large water reservoirs at different elevations to create gravitational potential energy (Rizzo, 2007). Bonaire lacks both the steep terrain to create sufficient elevation difference and the freshwater resources to operate such a system. Similarly, CAES requires stable underground caverns or sealed geological formations to store compressed air (Rizzo, 2007). Such formations do not exist on Bonaire, ruling out this technology as well.

As shown in Table 8, smaller-scale battery storage systems are the most widely applied in the Caribbean, with no significant deployment of large-scale pumped storage hydropower (PSH) or compressed air energy storage (CAES) projects reported up to 2016(Schelleman et al., 2016a). More recently, CGB installed a Battery Energy Storage System (BESS) with a discharge capacity of 14 MW and an energy capacity of 9 MWh, equivalent to roughly 35 minutes of maximum supply. While this system already plays an important role in supporting grid stability and power quality, it is not sufficient to meet the requirements of a fully renewable energy system on its own. To ensure a reliable power supply without relying on diesel backup, larger and longer-duration storage technologies will be needed. Technologies such as flow batteries, sodium-based batteries, hydrogen storage (Figure 16), as well as gravitational and thermal storage options (Figure 17), present promising solutions for providing long-duration flexibility. In such a system, the existing lithium-based BESS would continue to serve short-term balancing needs, while these additional technologies would address longer-duration storage requirements.

Table 8: Energy Storage Projects in the Caribbean (Schelleman et al., 2016a)



Nr.	Country	Technology	Rated Power in kW	Status
1	Antigua and Barbuda	Flow Battery	3,000	Operational
2	Aruba	Compressed Air Storage	1,000	Contracted
3	Aruba	Flywheel	5,000	Contracted
4	Bonaire	Nickel based Battery	3,000	Operational
5	British Virgin Islands	Electro-chemical	1000	Under Construction
6	Haiti	Electro-chemical	100	Under Construction
7	Haiti	Lithium-ion Battery	200	Operational
8	Haiti	Lithium-ion Battery	500	Under Construction
9	Martinique	Sodium based Battery	120	Operational
10	Martinique	Lithium-ion Battery	2,472	Operational
11	Puerto Rico	Sodium-ion Battery	250	Operational

7.3 Centralized vs. Decentralized storage: Trade-Offs

In designing Bonaire's storage architecture, an important trade-off arises between centralized and decentralized storage systems. As illustrated in Figure 28, centralized storage benefits strongly from economies of scale. The cost per kilowatt-hour decreases significantly as both discharge duration and system power rating increase (Pacific Northwest National Laboratory et al., 2022). Large scale installations, typically in the range of hundreds to thousands of megawatts and with durations of ten to one hundred hours, achieve lower unit costs through more efficient balance of system components, shared infrastructure and optimized power conversion systems. These installations are particularly effective for system-wide balancing, bulk energy shifting and evening peak coverage. However, they are geographically inflexible and are usually located at a centralized location.

Decentralized storage, which is installed at substations, distribution nodes or switching buses, does not benefit from the same economies of scale and therefore has a higher cost per kilowatt-hour. Its proximity to end users enables functions that centralized systems cannot easily provide, including localized balancing, reduction of transformer and feeder congestion and improved grid resilience (Fortenbacher et al., 2016). For Bonaire, this trade-off points toward a hybrid solution that combines large centralized systems to provide cost-effective bulk smoothing with smaller decentralized batteries placed at critical points in the distribution network to relieve local stress and support reliable operation.

It is important to recognize that although some non-battery technologies show very low costs per kilowatt-hour, this cost advantage is only achievable at very large scales. Technologies such as pumped storage hydropower, compressed air energy storage, hydrogen storage, gravitational storage and thermal storage are typically developed in the hundreds to thousands of megawatts range and are designed for long-duration applications. Their low unit costs rely on economies of scale that are only realized in large installations. As illustrated in Figure 28, these technologies are represented for specific combinations of power and duration that reflect their typical real-world use cases, rather than for small or distributed systems. As a result, they cannot realistically be deployed in decentralized locations, and in the case of Bonaire, even a centralized installation of this size would far exceed the island's system requirements. The absolute project sizes needed to achieve their cost advantage are simply too large for the scale of the island's electricity system.

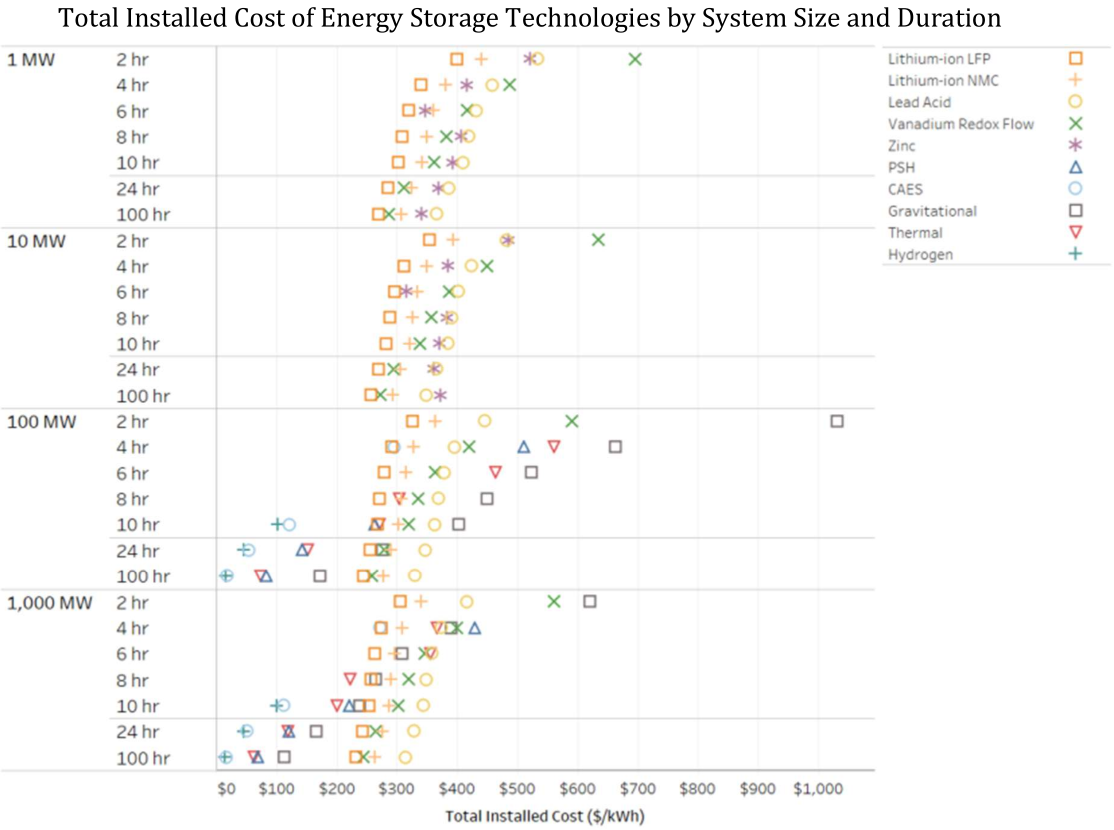


Figure 17: Comparison of total installed energy storage system (ESS) costs by technology, power rating, and discharge duration projected for 2030. The figure shows that costs per kWh decrease with larger system sizes and longer discharge durations, highlighting economies of scale across technologies such as lithium-ion, flow batteries, hydrogen, and pumped hydro (Pacific Northwest National Laboratory et al., 2022)

Chapter 8: Model implementation and scenario design

To design a fully renewable electricity system for Bonaire that remains reliable, affordable, and secure, this chapter develops a cost-optimization model that co-optimizes renewable generation with demand-side flexibility. The model inputs are directly derived from the preceding analyses: renewable energy potential), storage technologies and household demand flexibility. Network topology, demand growth trajectories, and intervention scenarios are then specified to represent the operational realities of Bonaire's grid. Together, these inputs provide the foundation for simulating future system pathways under different assumptions.

8.1 Month Selection and Cost Treatment

The model is run at hourly resolution for September 2030, representing a stress month that captures the energy system's performance under peak demand conditions. September is the hottest month of the year on Bonaire, as shown in the Appendix C1, which leads to the highest cooling-related electricity demand. Historical data confirm that both the highest overall demand and the annual peak loads occur during this month (Figure 3,4). In addition, solar and wind production are relatively among the lowest levels of the year (Figure 1). By focusing on this month, the modelling framework evaluates the system under the most challenging combination of high demand and reduced renewable resource availability, providing a robust test of system performance.

Because the model is run for a single representative month, all technology costs are expressed in monthly terms rather than annually. This ensures that the optimization reflects only the costs relevant to the simulated period, while maintaining a fair and consistent comparison between technologies with different technical lifetimes.

The cost calculation involves two main steps. First, investment costs (CAPEX) are annualized using a Weighted Average Cost of Capital (WACC) of 8.7 percent, which is the official value determined by the Netherlands Authority for Consumers and Markets (ACM) for energy companies in the Caribbean Netherlands for the period 2026–2028 (Netherlands Authority for Consumers and Markets, n.d.). This WACC is applied as a proxy for Bonaire to reflect realistic financing conditions for energy infrastructure in the region. Annualization is carried out using the Capital Recovery Factor (CRF):

$$\mathrm{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1},$$

where r is the WACC and n is the technical lifetime of the technology in years. The annualized CAPEX is then added to the annual Fixed O&M (FOM) cost to obtain the total annualized cost per megawatt:

$$\text{Annualized Cost} = \text{CAPEX} \times \text{CRF} + \text{Fixed O\&M}.$$

Second, this annualized cost is divided by 12 to obtain the monthlyized cost, expressed in \$/MW·month:

$$\text{Monthlyized Cost} = \frac{\text{Annualized Cost}}{12}.$$

This value represents the full cost of investment and fixed O&M for each technology during the one-month modelling period. The same procedure is applied consistently to both generation and storage technologies. This ensures that both generation and storage are treated on a comparable financial basis within the model. Using this approach allows technologies with different lifetimes, to be compared fairly during the stress month. Annualizing using the Caribbean Netherlands WACC and then monthlyizing ensures that long-lived assets are not over-penalized, and that costs correspond to the actual length of the simulation period.

Scenario cost comparisons are based on two key indicators: total monthly system cost and system cost per kilowatt-hour of electricity supplied. The total monthly system cost represents the sum of all investment, fixed operation and maintenance, and operational expenditures during the stress month of September 2030. This reflects the overall economic scale of each scenario while remaining fully consistent with the monthlyized cost inputs used in the model.

In addition, total system cost is divided by total electricity demand during the stress month to calculate a system cost per kilowatt-hour. This indicator provides a direct measure of the average cost of electricity supply and allows meaningful comparison across scenarios from a consumer perspective, since it is closely related to the level of cost that would ultimately need to be recovered through tariffs.

8.2 Network input assumptions

The representation of Bonaire's electricity network in PyPSA is based entirely on technical drawings, line inventories, and planning data provided by Water en Energiebedrijf Bonaire (WEB). The network model includes both the 30 kV transmission backbone and the 12 kV primary distribution system, which are represented as separate voltage levels and connected through transformers. All relevant nodes, including the Contour Global site, Morotin Wind Park, the two main substations, as well as distribution and switching stations, are represented as buses in PyPSA, see figure 18. Each bus is assigned its nominal voltage (30 kV or 12.2 kV) and geographic coordinates so that the network layout reflects the actual spatial structure of the island's grid. The plotted line geometries do not follow the exact physical cable routing but are represented as straight connections between buses; this has no effect on the power flow calculations.

Lines are used to connect buses operating at the same voltage level. For each line, the electrical resistance and reactance values from the WEB technical documentation, originally given in ohms, are converted to per unit values. This is necessary because PyPSA requires line impedances to be entered in per unit on a 1 MVA power base. Converting to per unit ensures that electrical parameters are expressed relative to a consistent reference, allowing the model to handle different voltage levels and component ratings correctly within a unified power flow formulation. Thermal ratings for each line are based on the nominal current capacity of the cables. For example, the 30 kV backbone cable with a current rating of 570 A corresponds to a power transfer capacity of approximately 29.6 MW, which is used as the line's maximum apparent power. This information is entered directly into the line component of PyPSA together with the electrical parameters.

Connections between buses of different voltage levels, specifically between the 30 kV transmission backbone and the 12 kV distribution network, are represented using transformers. Transformer parameters are derived from WEB nameplate data. The nominal voltages of the high- and low-voltage sides are set to

30 kV and 12.2 kV respectively. The series resistance and reactance are calculated from the copper losses and short-circuit voltage, converted to per unit, and entered into PyPSA. Transformer ratings are also taken directly from WEB data, ensuring that the transfer capacity between voltage levels reflects the existing infrastructure.

Investment costs for extendable network elements are based on WEB's inventory information. For the 30 kV backbone, WEB reports a construction cost of 26.16 USD per meter for an 8.4 km circuit with a capacity of 6.128 MW, corresponding to a total cost of roughly 220,000 USD or 35,900 USD per MW. This value is annualized using a 30-year lifetime and a WACC of 8.7 percent, then converted to a monthly value to match the one-month modelling horizon, resulting in approximately 283.5 USD per MW·month. This cost is assigned to the backbone connection between Morotin Wind and Contour Global, which is the only line set as extendable in the model. A preliminary capacity screening showed that under 2030 demand and resource assumptions, this corridor is the only part of the grid that may become limiting, while all other lines have sufficient capacity. As a result, all other lines and transformers are entered as fixed assets with their existing ratings.

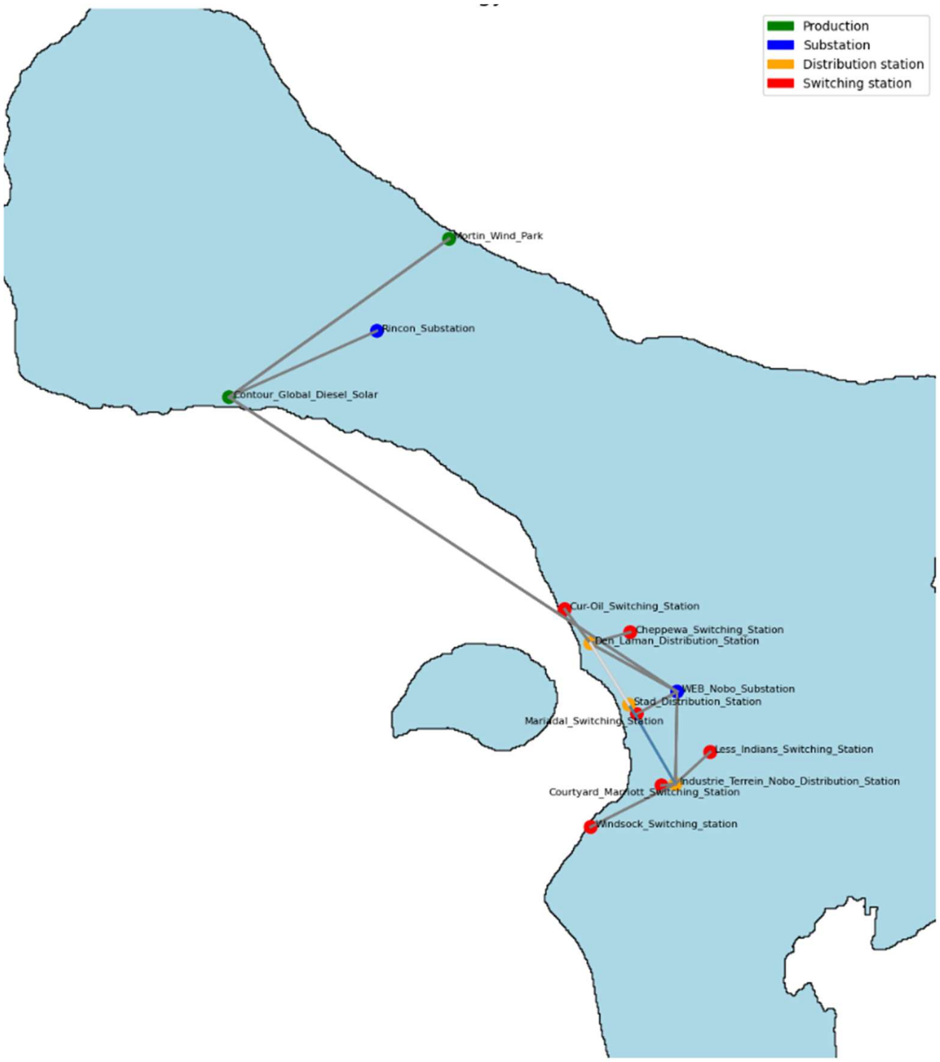


Figure 18: Visualization of the Bonaire energy network topology modelled in PyPSA. The map shows production sites (wind and diesel/solar), substations, distribution stations, and switching stations, as well as their interconnections across the island.

8.3 Generation input assumptions

The renewable energy potential analysis established that not all generation technologies are equally feasible for Bonaire. As already applied, wind and solar photovoltaics emerged as the most promising low-cost options, benefiting from Bonaire's consistently strong trade winds and high levels of solar irradiation. These resources can provide large volumes of energy, but since they are variable, the analysis concluded that they must be complemented by dispatchable technologies that can supply electricity during periods of low renewable availability. Three dispatchable options were assessed as feasible within Bonaire's context: concentrated solar power (CSP), biodiesel, and ocean thermal energy conversion (OTEC).

The input data for each generator, including capacity, resource availability profiles, efficiencies, and cost assumptions, are derived from a combination of Water en Energiebedrijf Bonaire (WEB) operational data, Contour Global cost data, and external technology cost sources such as NREL ATB 2024.

Solar PV is represented as a generator located at the Contour Global bus, with an initial installed capacity of 6 MW corresponding to the existing solar park. The hourly availability of the unit is defined using a per-unit production profile derived from measured output in September 2024. For each hour, this profile equals the measured output divided by the installed capacity, which ensures that the temporal variability of solar resources is accurately captured. The unit is assigned zero marginal cost, and capital cost assumptions are taken from Contour Global. It is set as extendable, allowing the model to add capacity if this proves cost-optimal under the scenario assumptions.

Wind generation is represented in a similar way. A generator is placed at the Morotin bus with a nominal capacity of 24 MW, reflecting the planned installation expected in 2026. Its hourly availability profile is derived from measured WEB wind production data for September 2024 and applied as a per-unit time series. The generator is assigned zero marginal cost and investment costs based on Contour Global and NREL ATB 2024. Like solar, the unit is extendable, allowing the optimization to determine whether additional wind capacity should be built.

Concentrated solar power (CSP) with ten hours of molten salt thermal storage is introduced as a new candidate technology and is represented using a StorageUnit component. This allows both the turbine and the molten salt storage to be modelled together within a single techno-economic entity while operating entirely on the electricity bus. The CSP unit is located at the Contour Global bus. Its inflow is derived from a direct normal irradiance profile representing a typical clear-sky day in September on Bonaire, which is repeated over the simulation period (see Appendix C3). The profile is scaled by a solar multiple of 2.4 to reflect an oversized collector field relative to the turbine. This formulation allows the turbine to generate at lower irradiance levels and to store excess thermal energy when irradiance is strong. The storage tank is treated as lossless, and the turbine's conversion efficiency is already included in the cost assumptions, which are expressed in dollars per megawatt of output power. To avoid double-counting efficiency losses, the round-trip efficiency of the storage unit is set to 1.0 in the PyPSA model. This approach allows CSP to be compared directly with other electricity generation technologies while accurately capturing its ability to shift solar energy to evening and nighttime hours. The CSP unit is set as extendable, allowing the optimizer to invest in capacity where it is economically advantageous.

Biodiesel generation is used in the scenario analysis (Section 8.6) and is represented by the existing diesel generator units at the Contour Global site, which are reused for renewable biodiesel. Since the physical infrastructure is already in place, these generators are assigned zero capital cost. A marginal cost is applied based on the estimated biodiesel fuel cost. To generate 1 MWh of electricity using biodiesel (B99–B100), a generator with 35% efficiency requires approximately 72 gallons of biodiesel.

At a fuel price of $4.08 per gallon, this results in a marginal cost of approximately $294 per MWh (Alternative Fuels Data Center: Fuel Prices, n.d.-b). To reflect their intended role as peaking units, the biodiesel generators are only made available for dispatch during high-demand hours. This is implemented using a binary availability profile, which is set to one when total system demand exceeds a defined threshold derived from the projected 2030 peak demand, and zero otherwise (see Appendix). In this way, biodiesel serves as a dispatchable reserve that supports the system only during critical peak periods.

Ocean Thermal Energy Conversion (OTEC) is also included in the scenario analysis (Section 8.6). It is represented as a fully dispatchable generator located at the Contour Global bus, reflecting its likely installation near the deep-water coastline. OTEC has no time-varying availability profile, as its energy source is essentially constant. Its initial capacity is set to zero, and it is modelled as an extendable technology in selected scenarios. The cost assumptions used for OTEC are defined by the scenario parameters and are listed in the generation cost table.

The complete set of generation technologies, including their installed capacities, extendibility, resource profiles, and monthly cost assumptions, is summarized in Table 9. This table provides the key techno-economic inputs used to represent generation technologies within the PyPSA model, linking renewable resource analysis, cost data, and operational characteristics to the overall system optimization framework.

Table 9. Monthlyized Generation Technology Costs Including CAPEX and Fixed O&M (WACC 8.7%)

Technology	**Initial nominal power (MW)**	**Extendable**	**Max generation per MW**	**CAPEX ($/MW)**	**Fixed O&M ($/MW·yr)**	**Lifetime (yr)**	**Monthlyized CAPEX + Fixed O&M Costs (WACC 8.7 %, $/MW·month)**	**Marginal cost ($/MWh)**
Existing Solar PV (CGB)	6	True	Hourly solar fraction (Sept 2024, WEB data)	$860,000 *(CGB)*	$45,430 *(CGB)*	30 *(NREL ATB 2024)*	$10,577	0
Existing Wind Park Morotin (CGB)	24	True	Hourly wind fraction (Sept 2024, WEB data)	$2,718,000 *(CGB)*	$49,650 *(CGB)*	30 *(NREL ATB 2024)*	$25,600	0
New CSP (10h storage)	0	True	DNI irradiance profile (scaled)	$5,978,000 *(NREL ATB 2024)*	$55,000 *(NREL ATB 2024)*	30 *(NREL ATB 2024)*	$51,788	0
Biodiesel (reuse diesel gensets)	0	Only in supply-flexibility scenario, see *§8.6*	Fully dispatchable	$0 *(existing asset)*	–	–	No extra cost as existing diesel generators are re-used	$294
New OTEC	0	Only in supply-flexibility scenario, see *§8.6*	Fully dispatchable	Price is scenario-dependent: - $25,900,000 -$15,000,000 - $11,020,000 *(see §8.6; Seungtaek et al., 2020)*	$145,200 *(Vega & Martin, 2024)*	30 *(Langer et al., 2021)*	- $216,619 - $130,547 - $99,119	0

8.4 Storage input assumptions

Storage is a key component of Bonaire's renewable transition, as it provides the flexibility required to balance variable renewable generation with demand. In the base configuration, the installed asset is the lithium-ion battery energy storage system at the Contour Global site, rated at 14 MW with 9 MWh of energy. In PyPSA this unit is represented as a StorageUnit, which holds both the power rating (p_nom) and the duration via max_hours (the implicit energy reservoir is e_nom = p_nom × max_hours). The storage duration is therefore the ratio of energy to power capacity, which for the existing system is approximately 0.64 h (9 MWh / 14 MW). Round-trip efficiencies are implemented as separate charging and discharging efficiencies so that their product equals the stated round-trip value. Because this asset already exists, its capital cost is set to zero and its marginal cost is also zero. The state of charge is initialized at zero and is not required to return to the same level at the end of the simulation period (cyclic_state_of_charge = False), reflecting real-world operation where the unit provides short-term balancing and peak support.

In the base case, a catalogue of additional storage technologies is included to capture the range of flexibility options plausibly available to Bonaire by 2030. Using the catalogue introduced in Section 7.3, the model includes lithium-ion chemistries (lithium iron phosphate and nickel manganese cobalt), lead-acid, vanadium redox flow, zinc, gravitational, thermal, and hydrogen systems. Consistent with Section 7.2, compressed-air energy storage (CAES) and pumped-storage hydropower (PSH) are excluded as not feasible on Bonaire. To keep the focus on realistic build sizes, the base scenario limits battery discharge durations to short- to medium-duration options (2, 4, 6, 8, 10 hours) and excludes the 24-hour and 100-hour variants from the initial optimization. For non-battery options that are only technically and economically viable at bulk scale, the model uses 100 MW entries and excludes 1,000 MW cases as disproportionate for Bonaire. Preliminary optimisations produced a hydrogen build of about 42 MW and a gravitational build below 2 MW. A 42 MW hydrogen plant can be technically feasible, but our catalogue costs are benchmarked at 100 MW; applying those unit costs to a sub-100 MW build would understate expenditure. To keep the modelling consistent with the cost basis, hydrogen is retained with a 10% cost adder as a proxy for diseconomies at smaller scale, avoiding over-selection driven by optimistic scaling. By contrast, gravitational and thermal storage is not realistic for Bonaire given the site and scale requirements implied by their cost benchmarks, so these technologies were removed from the candidate set. All other inputs remain unchanged.

In the base case with centralized storage, each catalogue technology is represented as an extendable StorageUnit attached to the Contour Global bus. To reflect economies of scale, cost inputs for batteries use the 10 MW scale, while non-battery options (gravitational, hydrogen, thermal) use the 100 MW scale. In a separate decentralized scenario, battery costs are taken from the 1 MW scale to reflect the higher per-MW cost of smaller systems. Capital costs are entered in $/MW·month (monthlyised CAPEX plus fixed O&M using the WACC and lifetimes defined earlier), and marginal costs are set to zero in line with the treatment of renewable generators. PyPSA sets a storage unit's energy capacity automatically as the product of its power rating and its duration. In the catalogue, the duration is fixed for each technology, while the power rating (p_nom, in MW) is a decision variable. In this way, the model jointly determines which technology and duration to use and how large it builds.

The full set of modelled storage options, including their round-trip efficiencies, lifetimes, and discharge durations, is summarized in Table 10 (Pacific Northwest National Laboratory et al., 2022). See Appendix H for the cost breakdowns that underpin the monthlyised inputs.

Table 10: storage Technologies, round-trip efficiencies, and Monthlyized CAPEX + Fixed O&M Costs (WACC 8.7 %, $/MW·month) in the Bonaire Energy System Model, marginal cost is assumed to be 0 $/MWh (Pacific Northwest National Laboratory et al., 2022).

Technology	Round-trip Efficiency (%)	Lifetime years (years)	Duration (hours)	1 MW ($/MW·month)	10 MW ($/MW·month)	100 MW ($/MW·month)
Li-ion BESS (existing)	85	—	0.64 (14 MW / 9 MWh)	—	—	—
Li-Ion NMC	85	15	2	9,284	8,281	—
			4	16,031	14,709	—
			6	23,178	21,494	—
			8	29,805	27,734	—
			10	35,931	33,663	—
Li-Ion LFP	85	15	2	8,403	7,413	—
			4	14,316	13,079	—
			6	20,647	19,000	—
			8	26,373	24,523	—
			10	31,830	29,680	—
Lead Acid	78	10	2	14,050	12,668	—
			4	24,086	22,221	—
			6	34,796	32,231	—
			8	44,611	41,635	—
			10	53,732	50,433	—
Vanadium Redox Flow	65	12	2	16,306	14,796	—
			4	22,783	21,007	—
			6	31,163	28,890	—
			8	37,569	35,060	—
			10	42,115	39,539	—
Zinc	70	15	2	11,431	10,682	—
			4	18,607	17,350	—
			6	26,434	24,701	—
			8	33,929	31,846	—
			10	41,092	38,786	—
Hydrogen	35	30	10	—	10,322	9,684

8.5 Demand input assumptions

The load inputs for the 2030 model are derived by scaling the measured hourly demand profiles of 2024. This approach ensures that the temporal distribution of demand across the day and week is preserved, while the overall magnitude is increased to reflect future growth. Two alternative trajectories were applied. The first scenario, referred to as G3, assumes an annual growth rate of 3%, consistent with Bonaire's historical trend. The second scenario, G6, represents a high-growth case of 6% per year, reflecting more rapid population expansion, accelerated tourism development, and increasing electrification of transport and other end uses.

Over the six-year period from 2024 to 2030, the G3 scenario results in demand levels that are approximately 19.4% higher. Under the G6 scenario, demand rises by around 41.8%. Growth is not distributed evenly across the network. Instead, load increases are allocated at the level of individual substations and switching stations according to known development plans provided by the Water en Energiebedrijf

Bonaire. Planned residential areas, hotel expansions, new commercial facilities, and industrial customers are incorporated and their expected capacity increases are assigned to the relevant buses in the model. This produces a more realistic representation of spatial demand growth than a uniform scaling approach, See table 11.

Certain exceptions are handled separately. The Mariadal Hospital is treated as critical infrastructure whose demand must always be fully supplied and is therefore excluded from the residential and commercial growth allocation. The Windsock substation is excluded entirely, as no new developments are expected in its service area. For all other substations, growth is calculated by combining specific project commitments, expressed as projected megawatt increases by 2030, with residual scaling needed to meet the average annual growth assumptions of the G3 and G6 scenarios.

Table 11: Substation-Level Load Growth Projections (2024–2030) under G3 and G6 Scenarios (WEB, internal data and own elaboration)

Station	**Peak 2024 (MW)**	**Known projects to 2030 (MW)**	**% increase (projects only)**	**Low growth (G3) total %**	**High growth (G6) total %**
Rincon Substation	1.70	0.32	18.8%	9.45%	20.47%
Mariadal Hospital Switching Station	4.84	4.01	82.9%	82.9% (critical)	82.9% (critical)
Stad Distribution Station	4.67	0.36	7.7%	3.87%	8.34%
Den Laman Distribution Station	2.98	0.24	8.1%	4.07%	8.77%
Cur-Oil Switching Station	3.42	0.71	20.8%	10.43%	22.49%
Cheppewa Switching Station	3.47	2.60	74.9%	37.63%	81.13%
Industrie Terrein Nobo Distribution	4.82	1.06	21.9%	11.01%	23.74%
Less Indians Switching Station	3.62	0.92	25.4%	12.76%	27.52%
Courtyard Marriott Switching Station	2.22	2.92	131.5%	66.02%	142.43%
Windsock Switching Station	1.49	0.00	0%	0%	0%
Average (excl. Mariadal, Windsock)	–	–	38.6%	19.4%	41.9%

8.6 Intervention Scenarios

As analysed in the report, flexibility options are essential in a power system dominated by intermittent wind and solar to guarantee reliability and cost efficiency. On the generation side, two dispatchable options were identified: biodiesel (using the existing diesel engines with biodiesel fuel) and OTEC (Ocean Thermal Energy Conversion). On the demand side, residential households have shown willingness to adapt consumption to time-of-use tariffs. With the expected growth in electric vehicles (EVs), demand-side flexibility becomes even more impactful. From the storage perspective, the storage analysis demonstrated that different storage technologies can provide additional reliability. Localized flexibility can be further enhanced through the deployment of decentralized storage options. In this section, four intervention strategies are defined. Each is tested across the stress month of September and under both demand growth forecasts (G3: +3% annually, G6: +6% annually).

To structure the analysis, four scenario groups are defined. The first is the Business-as-Usual baseline, which represents a centralized system with no demand-side flexibility, no decentralized storage, and without enabling alternative technologies such as OTEC or biodiesel. This provides a reference against which the value of flexibility and decentralization can be measured.

Demand-side flexibility

Demand-side management (DSM) is represented with three scenarios that use the same time windows for all actions: households switch from air-conditioning to fan cooling from 19:00 to 22:00, and electric-vehicle charging is shifted to 03:00 to 06:00. In the Low-DSM scenario, 42% of households participate only in evening cooling. With 8,267 households in 2024 and a 2030 growth factor of 19.4%, this gives 9,871 households in 2030, of which 4,146 participate. Each participating home reduces 1.75 kW by switching from AC to a fan, resulting in a system reduction of 7.26 MW from 19:00 to 22:00. EV charging is unchanged in this scenario. In the Mid-DSM scenario, the same 42% of households participate in both evening cooling and EV charging. The evening cooling reduction remains 7.26 MW from 19:00 to 22:00, and 5.98 MW of EV load is shifted from the evening to the 03:00–06:00 window. In the High-DSM scenario, participation rises to 68% for both households and EVs. The evening cooling reduction increases to 11.75 MW from 19:00 to 22:00, and 9.68 MW of EV charging is shifted to 03:00–06:00. All reductions and shifts are allocated across buses in proportion to the residential load shares.

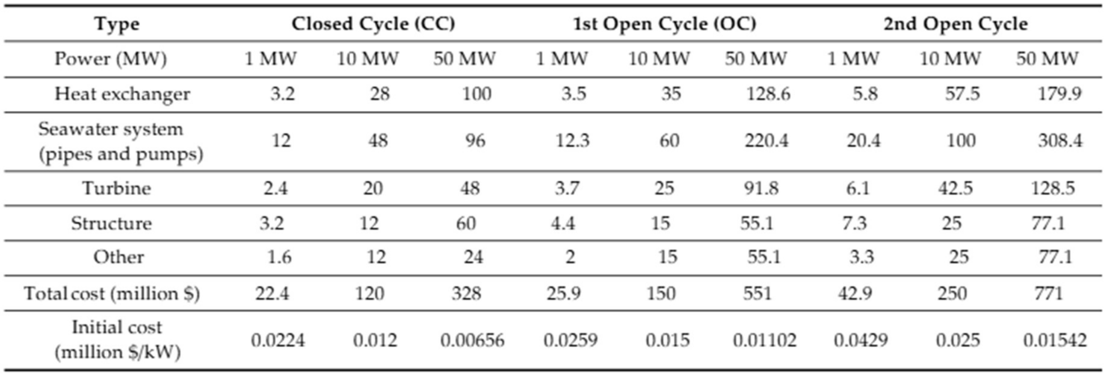
Storage flexibility

The third group explores Decentralized Storage Expansion, in which storage can be built both centrally and at local nodes. Centralized storage is located at the Contour Global bus and benefits from economies of scale; for batteries, costs are taken from the 10 MW assumptions used earlier, making central builds cheaper per unit but geographically inflexible. Decentralized storage is deployed at distribution and switching buses and uses the 1 MW battery cost assumptions, reflecting the higher per-MW cost of smaller units while enabling balancing closer to demand and local renewable generation. Hydrogen was excluded as it resulted in decentralized storage of 3MW, which makes it technically unfeasible.

Supply-side flexibility

On the supply side, two flexible options are examined: ocean thermal energy conversion (OTEC) and biodiesel. OTEC is considered in both first and second open-cycle designs, selected for Bonaire because they avoid ammonia as a working fluid and therefore pose lower environmental risks than closed-cycle systems. The second open-cycle variant co-produces freshwater alongside electricity more efficiently, which. To reflect cost uncertainty, three capital-cost benchmarks from Table 12 are used: a high case of $25.9 million for a 1 MW first open-cycle and 10MW second open-cycle plants; a medium case of $15 million applied to 10 MW first open-cycle and 50 MW second open-cycle plants; and a low case of $11.02 million for a 50 MW first open-cycle plant (Seungtaek et al., 2020). All OTEC units also bear fixed annual maintenance costs of $145,200 per MW-year (Vega & Martin, 2024). Capital and fixed O&M are included via the monthlyized cost inputs defined earlier, see table 9.

Table 12: Projected costs of Ocean Thermal Energy Conversion (OTEC) technologies at different plant sizes and configurations (Seungtaek et al., 2020). The figure compares three main types: (i) Closed-cycle systems, which use a working fluid such as ammonia to generate electricity but do not produce freshwater; (ii) ***First open-cycle systems****, which use seawater directly as the working fluid, producing both electricity and freshwater through low-pressure evaporation and condensation; and (iii)* ***Second open-cycle systems****, which also co-produce freshwater but are optimized for higher water output and greater efficiency, albeit with more technical complexity. Both open-cycle designs are environmentally preferable to closed-cycle, as they avoid synthetic working fluids and directly support Bonaire's energy–water nexus.*



Type	Closed Cycle (CC)			1st Open Cycle (OC)			2nd Open Cycle		
Power (MW)	1 MW	10 MW	50 MW	1 MW	10 MW	50 MW	1 MW	10 MW	50 MW
Heat exchanger	3.2	28	100	3.5	35	128.6	5.8	57.5	179.9
Seawater system (pipes and pumps)	12	48	96	12.3	60	220.4	20.4	100	308.4
Turbine	2.4	20	48	3.7	25	91.8	6.1	42.5	128.5
Structure	3.2	12	60	4.4	15	55.1	7.3	25	77.1
Other	1.6	12	24	2	15	55.1	3.3	25	77.1
Total cost (million $)	22.4	120	328	25.9	150	551	42.9	250	771
Initial cost (million $/kW)	0.0224	0.012	0.00656	0.0259	0.015	0.01102	0.0429	0.025	0.01542

Biodiesel, by contrast, leverages the existing Contour Global diesel gensets, which are assumed to be converted to operate on biodiesel. Its role is strictly limited to rare peak events, preserving it as a last-resort backup rather than a continuous supply option. As shown in Figure 19 (WEB internal data, Load Curve 2024), the current system peak reaches 26.26 MW. By 2030, under different growth trajectories, peak demand rises to 31.36 MW in the G3 (+3% growth) scenario and to 37.25 MW in the G6 (+6% growth) scenario. Biodiesel generation is therefore only dispatched above 28.36 MW in G3 and above 34.25 MW in G6, equating to roughly 213 hours of operation per year. The associated cost of supplying this emergency backup is estimated at USD 62622 annually, reflecting the premium price of biofuel. This makes biodiesel an expensive but necessary form of supply-side flexibility to ensure system reliability under peak stress.

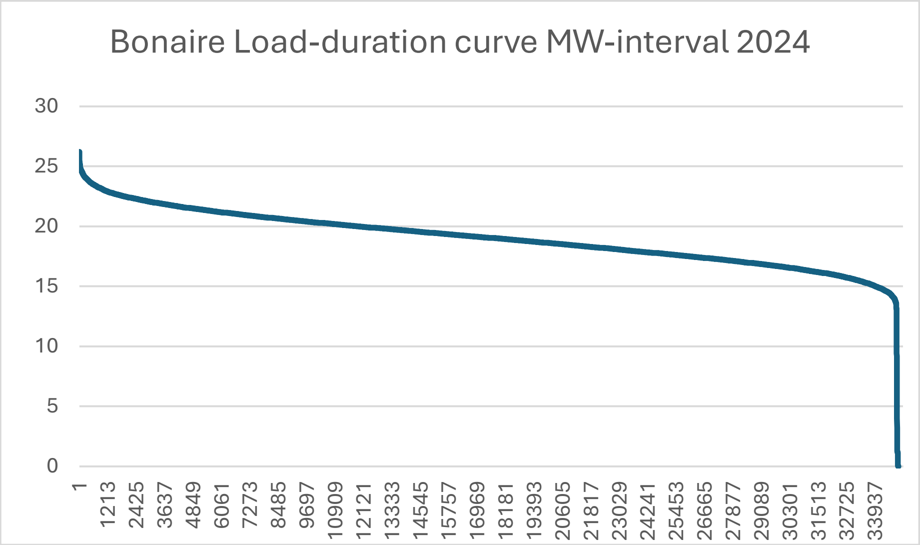


Figure 19: The 2024 load duration curve for Bonaire, showing peak demand at ~26.3 MW and long stretches of lower loads. The sharp peaks highlight the need for dispatchable backup generation to complement variable wind and solar. In future projections, demand growth raises these peaks, creating a stronger case for firm resources such as biodiesel and OTEC. Biodiesel relies on imported renewable fuel, making it sensitive to fuel costs, while OTEC has no fuel cost but carries high upfront capital and lifetime maintenance expenses (WEB internal data).

Chapter 9: Results

This chapter aims to answer the last sub-question: ***What is the cost-optimal electricity mix for Bonaire that integrates renewable energy sources and flexibility options to ensure reliability?***

This chapter presents the results of the system optimization runs for Bonaire, using September as the representative stress month under both low-growth (G3) and high-growth (G6) demand scenarios. The results are structured around the defined scenarios: (1) the baseline with current wind, solar, and storage; (2) demand-side flexibility cases; (3) decentralized storage expansion; and (4) flexible generation with OTEC and biodiesel. In the first three sets of scenarios, OTEC and biodiesel remain closed and not expandable, so the system relies entirely on variable renewables and storage. For each case, the graphs present the optimized capacity mix and associated system costs, showing how different strategies affect the balance between solar, wind, storage, and dispatchable options.

9.1 Baseline scenario: current wind, solar and centralized storage

Figure 20 shows the baseline scenario for 2030, which represents the system configuration where Bonaire continues to rely on its existing renewable energy resources, with solar PV and wind as the main generation sources and CSP as the only new firm generation option. This scenario serves as the reference for comparing alternative demand growth and intervention pathways.

For the September stress month, solar PV dominates capacity expansion, reaching 138 MW under G3 and 164 MW under G6, highlighting its central role in the system. Wind capacity remains constant at 24 MW in both cases, while CSP contributes a small share of 6 MW under G3 and 8 MW under G6, mainly providing evening generation and flexibility through its built-in storage.

Storage capacity expands significantly to balance variable solar and wind output. Under G3, the system includes 43 MW of 4 h lithium-ion batteries and 44 MW of 10 h hydrogen storage. Under G6, storage expands to 47 MW and 48 MW, respectively. These longer-duration systems play a key role in managing daily fluctuations, supported by the existing 14 MW / 9 MWh BESS. OTEC and biodiesel are not included in this scenario and do not contribute to the generation mix.

Monthlyized system costs represent the capital investment and fixed O&M costs converted into equivalent monthly payments, using a weighted average cost of capital of 8.7% and the technical lifetime of each technology. To express these costs on a per-unit basis, the total monthlyized cost is divided by the amount of electricity generated during the month. The resulting value in $/kWh reflects the investment and fixed cost component of the production cost, which is a key input for tariff setting. It indicates how much of the electricity price is needed to cover the capital and fixed costs of the system. Under G3, monthlyized added capacity costs amount to $2.71 million per month, equivalent to $0.1541/kWh. Under G6, costs increase to $3.24 million per month, or $0.1609/kWh. While the overall technology mix remains broadly similar across the two growth paths, higher demand in G6 requires larger capacity additions, resulting in higher monthlyized costs.

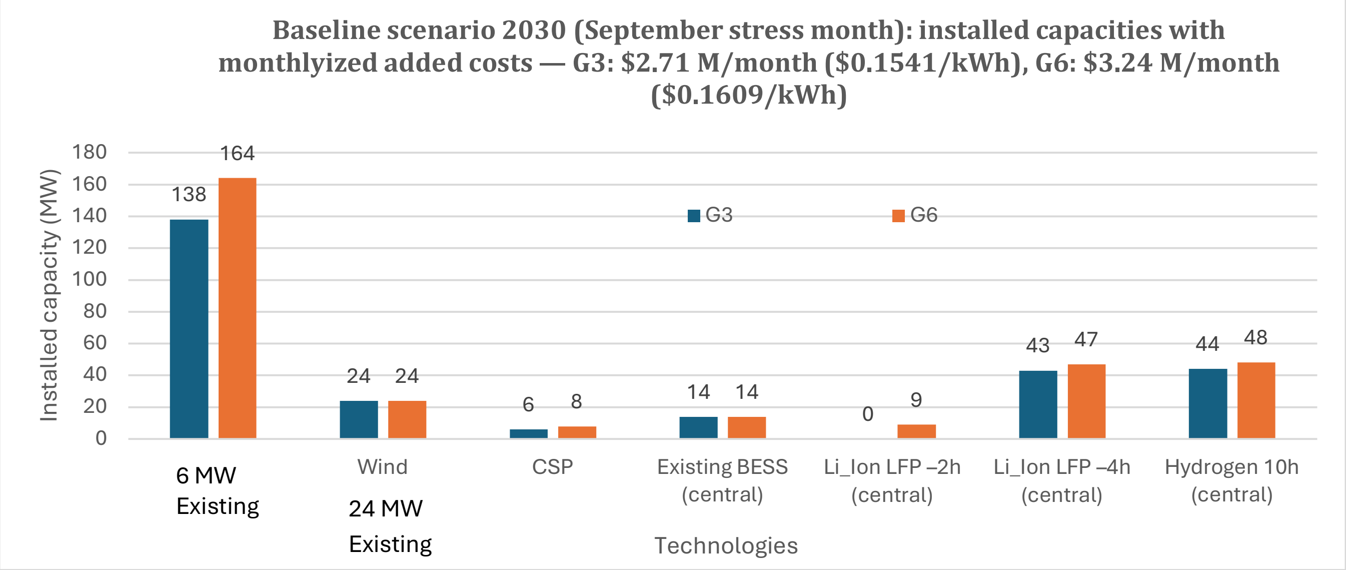


Figure 20: Baseline scenario 2030 (September stress month). Installed capacities of solar, wind, CSP, and centralized storage under the G3 and G6 growth scenarios, with total monthlyized system costs of $2.71 million ($0.1541 /kWh) and $3.24 million ($0.1609 /kWh), respectively (model results).

9.2 Demand flexibility under low growth (G3)

Figure 21 shows how demand-side flexibility reshapes the system compared to the baseline G3 scenario during the September stress month. In the baseline case without demand-side measures, the system relies on 138 MW of solar PV, 24 MW of wind, 6 MW of CSP, and a large portfolio of storage technologies to meet the sharp evening cooling peak. Monthlyized added capacity costs amount to $2.71 million per month ($0.1541 per kWh).

Demand-side flexibility is represented by two actions. First, households use ventilators instead of air conditioning between 19:00 and 20:00, reducing evening cooling loads. Second, electric vehicle charging is shifted from 19:00–22:00 to 03:00–06:00, moving the load to early morning. These measures reduce evening peak demand and reshape system needs.

With low flexibility (42% participation), solar PV capacity decreases to 128 MW, while storage requirements fall to 37 MW of 4 h lithium-ion and 41 MW of 10 h hydrogen. Monthlyized costs fall to $2.50 million per month ($0.1498 per kWh). The medium flexibility case builds on this by adding more managed EV charging participation, further reducing evening peaks. Solar PV capacity falls to 121 MW, storage decreases to 37 MW of 4 h lithium-ion and 38 MW of 10 h hydrogen, and monthlyized costs decline to $2.34 million per month ($0.1461 per kWh).Under high flexibility (68% participation), solar PV capacity drops to 110 MW, storage falls to 28 MW of 4 h lithium-ion and 33 MW of 10 h hydrogen, and monthlyized costs decrease to $2.11 million per month ($0.1406 per kWh).

These results show that increasing demand-side flexibility through reduced cooling loads and shifting EV charging lowers renewable and storage capacity requirements, resulting in smoother load patterns and lower system costs during the stress month.

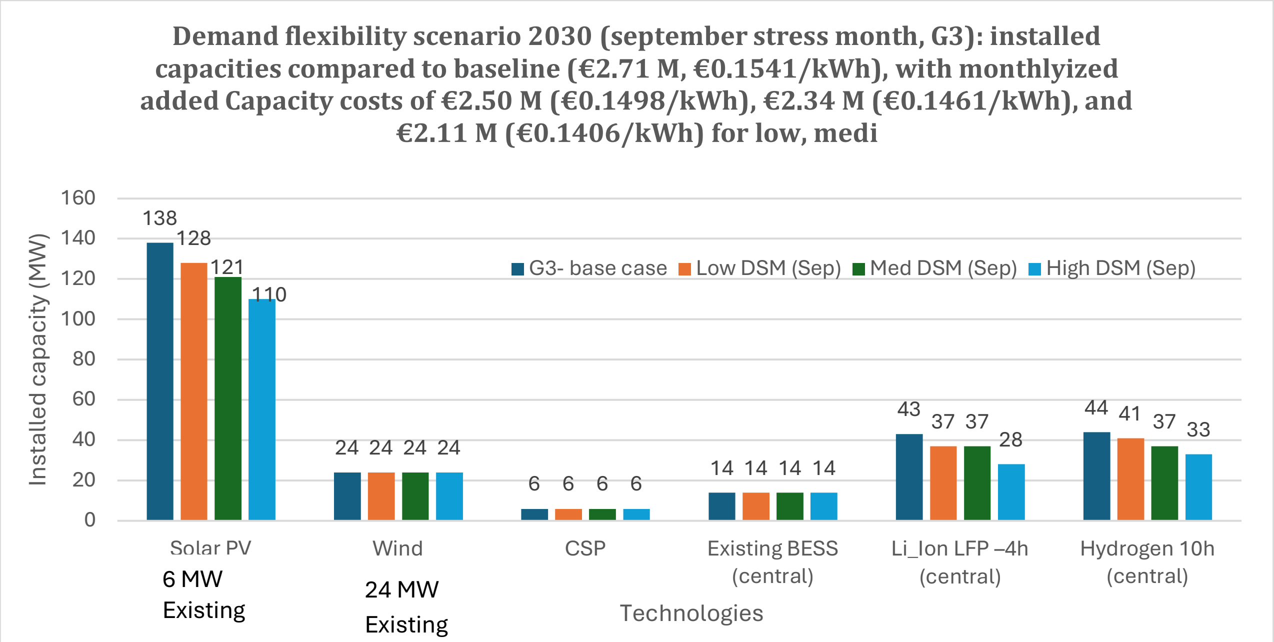


Figure 21: Demand Flexibility Scenario 2030 (September stress month, G3). Installed capacities of solar, wind, CSP, and centralized storage under low, medium, and high DSM assumptions compared to the baseline scenario. The baseline monthlyized added capacity cost is $2.71 million ($0.1541/kWh). Under low, medium, and high DSM levels, the total monthlyized added capacity costs decrease to $2.50 million ($0.1498/kWh), $2.34 million ($0.1461/kWh), and $2.11 million ($0.1406/kWh), respectively (model results).

9.3 Demand flexibility under high growth (G6)

Figure 22 shows how demand-side flexibility reshapes the system under the G6 growth pathway during the September stress month. In the baseline case without demand-side measures, the system relies on 164 MW of solar PV, 24 MW of wind, 8 MW of CSP, and a large storage portfolio, including 47 MW of 4 h lithium-ion batteries and 48 MW of 10 h hydrogen storage. Monthlyized added capacity costs amount to \$3.24 million per month (\$0.1609 per kWh). The same flexibility measures are applied: households use ventilators instead of air conditioning between 19:00 and 20:00, and electric vehicle charging is shifted from 19:00–22:00 to 03:00–06:00.

With low flexibility (42% participation), solar PV capacity decreases to 155 MW, storage falls to 43 MW of 4 h lithium-ion and 44 MW of 10 h hydrogen, and monthlyized costs decrease to \$2.99 million per month (\$0.1568 per kWh).In the medium flexibility case, solar PV capacity decreases to 146 MW, storage falls to 38 MW of 4 h lithium-ion and 41 MW of 10 h hydrogen, and monthlyized costs decline to \$2.83 million per month (\$0.1538 per kWh).Under high flexibility (68% participation), solar PV capacity falls to 110 MW, storage decreases to 34 MW of 4 h lithium-ion and 37 MW of 10 h hydrogen, and monthlyized costs fall to \$2.58 million per month (\$0.1490 per kWh).

These results demonstrate that even under high demand growth, demand-side flexibility significantly reduces capacity requirements and monthlyized costs. By lowering evening cooling loads and shifting EV charging to off-peak hours, the system requires less solar and storage capacity, resulting in lower costs and a more balanced technology mix during the stress month.

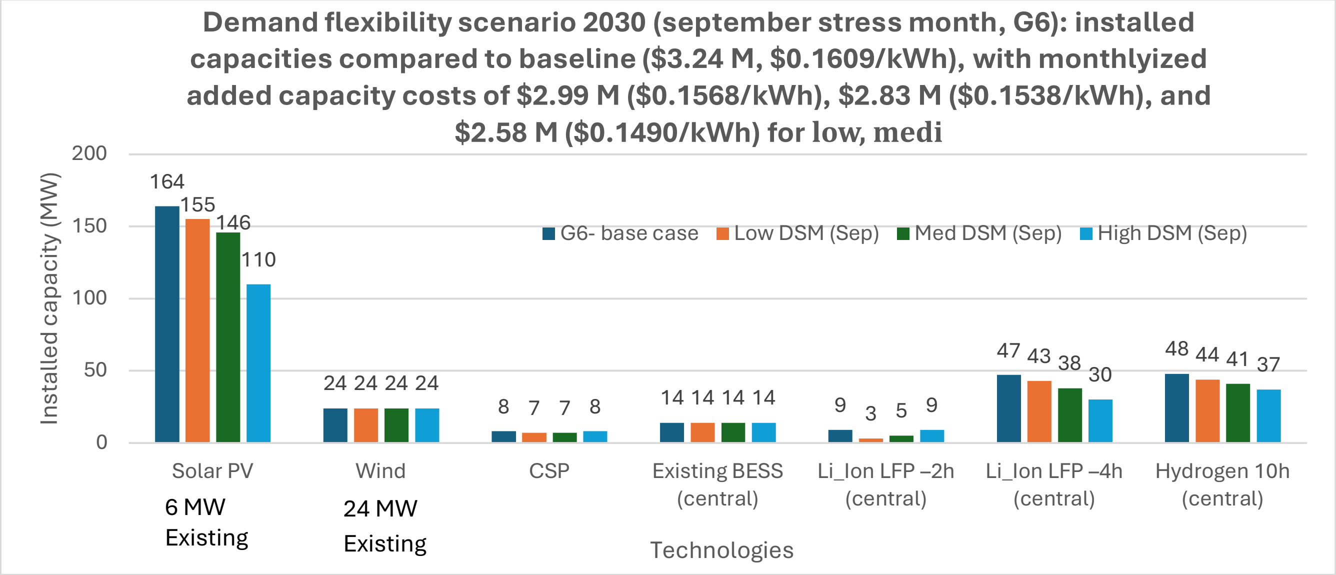


Figure 22: Demand Flexibility Scenario 2030 (September stress month, G6). Installed capacities of solar, wind, CSP, and centralized storage under low, medium, and high DSM assumptions compared to the baseline scenario. The baseline monthlyized added capacity cost is \$3.24 million (\$0.1609/kWh). Under low, medium, and high DSM levels, the total monthlyized added capacity costs decrease to \$2.99 million (\$0.1568/kWh), \$2.83 million (\$0.1538/kWh), and \$2.58 million (\$0.1490/kWh), respectively (model results).

9.4 Decentralized storage scenario under low (G3) and high (G6) growth

This scenario illustrates the decentralized storage expansion case, shown in Figure 23, where storage is allowed to be installed at locations other than the main centralized site at ContourGlobal. The figure shows that the overall generation mix remains almost identical to the baseline. Solar PV reaches 138 MW under G3 and 165 MW under G6, while wind capacity remains at 24 MW in both cases. CSP contributes 6 MW under G3 and 7–8 MW under G6. These values match the baseline scenario, indicating that generation planning is unaffected by this intervention.

The key difference is visible on the far right of the figure, where a 2 MW 2 h lithium-ion unit is added at the Morotín wind park under both G3 and G6. Locating storage at the wind site allows temporary storage of wind production closer to where it is generated. This reduces immediate power transfers through the grid, which can help alleviate network stress and delay or reduce the need for future grid reinforcements. Effectively, this targeted placement acts as a local buffer for wind output.

No additional storage is added near other generation stations or within the distribution network. This reflects that centralized storage remains the preferred option at this stage, as the grid is not yet congested and centralized facilities benefit from economies of scale.

Monthlyized system costs are nearly identical to the baseline. Under G3, costs are $2.70 million per month ($0.1536 per kWh), compared to $2.71 million per month ($0.1541 per kWh) in the baseline. Under G6, costs are $3.23 million per month ($0.1605 per kWh), compared to $3.24 million per month ($0.1609 per kWh). This confirms that adding storage at the wind park does not significantly affect total system costs but offers operational and grid benefits related to integrating wind energy locally.

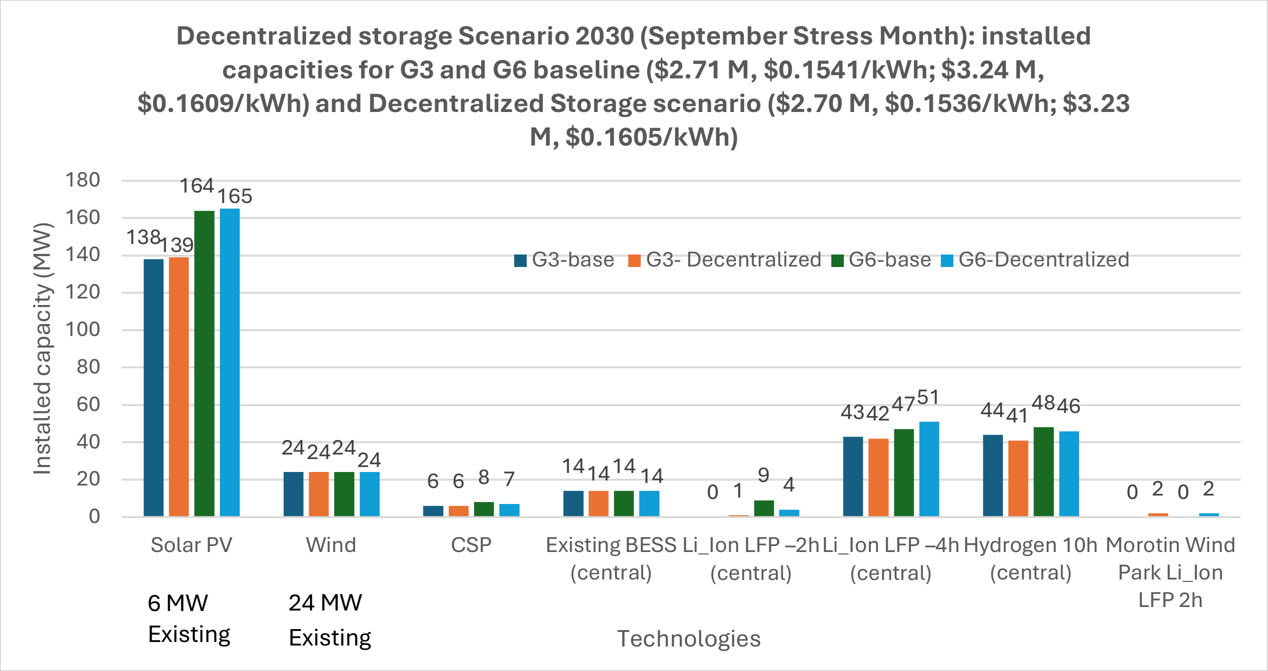


Figure 23: Decentralized Storage Scenario 2030 (September stress month). Installed capacities of solar, wind, CSP, and storage for G3 and G6 under both baseline and decentralized storage configurations. The total monthlyized added capacity costs amount to $2.71 million ($0.1541/kWh) for the G3 baseline and $3.24 million ($0.1609/kWh) for the G6 baseline. For the decentralized storage cases, the costs are $2.70 million ($0.1536/kWh) for G3 and $3.23 million ($0.1605/kWh) for G6, respectively (model results).

9.5 Flexible generation scenario under low growth (G3)

This scenario examines the flexible generation case for the G3 low growth pathway, illustrated in Figure 24. In this scenario, OTEC and biodiesel are introduced as dispatchable resources to complement the variable output of solar and wind. Five configurations are compared: the baseline without OTEC, OTEC at 11.02 M$/MW, OTEC at 15 M$/MW, OTEC at 25.9 M$/MW, and a biodiesel backup unit with a fixed capacity of 3 MW. Each configuration is optimized separately to assess how different cost assumptions affect the generation mix and overall system costs.

At a low OTEC investment cost of 11.02 M$/MW, the model installs 21 MW of OTEC capacity. This provides firm renewable output during periods of low solar and wind generation, allowing the system to reduce both new solar PV and storage investments compared to the baseline. Monthlyized system costs fall to 2.67 M$/month (0.1325 $/kWh), making this the least-cost configuration for the G3 pathway. At a medium cost of 15 M$/MW, the model installs 5 MW of OTEC capacity. The system mix remains similar to the baseline, with monthlyized costs of 2.61 M$/month (0.1485 $/kWh). At the highest cost level of 25.9 M$/MW, OTEC is not selected, and the system reverts entirely to the baseline configuration dominated by 138 MW of solar PV, 24 MW of wind, and centralized storage. Monthlyized costs are 2.71 M$/month (0.1541 $/kWh), identical to the baseline. These results show that OTEC becomes attractive only under optimistic cost assumptions. The biodiesel backup case adds 3 MW of firm capacity, which operates only during rare peak demand events. During the September stress month, biodiesel is dispatched for 3 hours and produces 9 MWh at a variable cost of 2,646 $. Because of its very limited use, the capacity mix remains unchanged and the total monthlyized cost is 2.70 M$/month (0.1534 $/kWh), essentially the same as the baseline. Biodiesel therefore functions as a targeted reliability measure for exceptional peaks rather than influencing long-term capacity expansion.

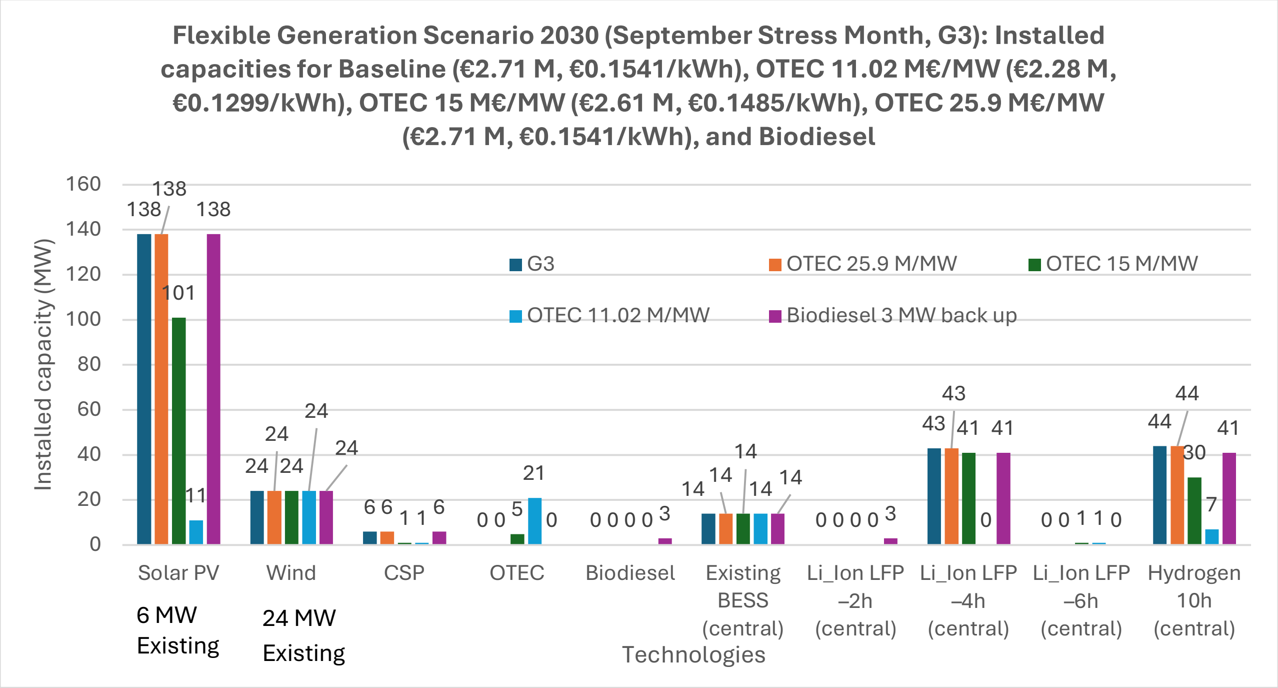

Flexible Generation Scenario 2030 (September Stress Month, G3): Installed capacities for Baseline (€2.71 M, €0.1541/kWh), OTEC 11.02 M€/MW (€2.28 M, €0.1299/kWh), OTEC 15 M€/MW (€2.61 M, €0.1485/kWh), OTEC 25.9 M€/MW (€2.71 M, €0.1541/kWh), and Biodiesel

Figure 24: Flexible Generation Scenario 2030 (September stress month, G3). Installed capacities of solar, wind, CSP, OTEC, and biodiesel generation are compared for five configurations: (i) baseline without OTEC, (ii) OTEC at 11.02 M€/MW, (iii) OTEC at 15 M€/MW, (iv) OTEC at 25.9 M€/MW, and (v) biodiesel 3 MW backup. The total monthlyized added capacity costs amount to €2.71 million per month (€0.1541/kWh) for the baseline, €2.28 million per month (€0.1299/kWh) for OTEC at 11.02 M€/MW, €2.61 million per month (€0.1485/kWh) for OTEC at 15 M€/MW, €2.71 million per month (€0.1541/kWh) for OTEC at 25.9 M€/MW, and €2.70 million per month (€0.1534/kWh) for biodiesel backup (model results).

9.6 Flexible Generation Options under High Growth (G6)

This scenario examines the flexible generation case for the G6 high growth pathway, illustrated in Figure 25. In this scenario, OTEC and biodiesel are introduced as dispatchable resources to complement the variable output of solar and wind. Five configurations are compared: the baseline without OTEC, OTEC at 11.02 M€/MW, OTEC at 15 M€/MW, OTEC at 25.9 M€/MW, and a biodiesel backup unit with a fixed capacity of 3 MW. Each configuration is optimized separately to assess how different cost assumptions affect the generation mix and overall system costs.

At a low OTEC investment cost of 11.02 M€/MW, the model installs 25 MW of OTEC capacity. This provides firm renewable output during periods of low solar and wind generation, which allows the system to reduce both new solar PV installations and storage capacity compared to the baseline configuration. As a result, monthlyized system costs decline to 2.67 M€/month (0.1325 €/kWh), making this the least-cost configuration for the G6 pathway. This result highlights the potential of OTEC to diversify the generation portfolio and lower total system costs if future technology prices fall to optimistic levels. When OTEC costs are assumed to be 15 M€/MW, the model installs 7 MW of OTEC capacity. The system configuration remains close to the baseline, and monthlyized costs reach 3.10 M€/month (0.1536 €/kWh). At the highest cost level of 25.9 M€/MW, OTEC is not selected, and the system reverts entirely to the baseline dominated by 164 MW of solar PV, 24 MW of wind, and centralized storage. Monthlyized costs in this case are 3.24 M€/month (0.1609 €/kWh), identical to the baseline result. These findings show that OTEC is only competitive under optimistic cost assumptions, particularly in a high growth context.

The biodiesel backup case adds 3 MW of firm capacity, but it is not dispatched during the September stress month. Hours used, energy produced, and variable costs are all zero. Because of this, the capacity mix and monthlyized system cost remain unchanged compared to the baseline at 3.24 M€/month (0.1609 €/kWh). Biodiesel therefore functions as reserve capacity for extreme conditions rather than influencing the generation mix or system costs.

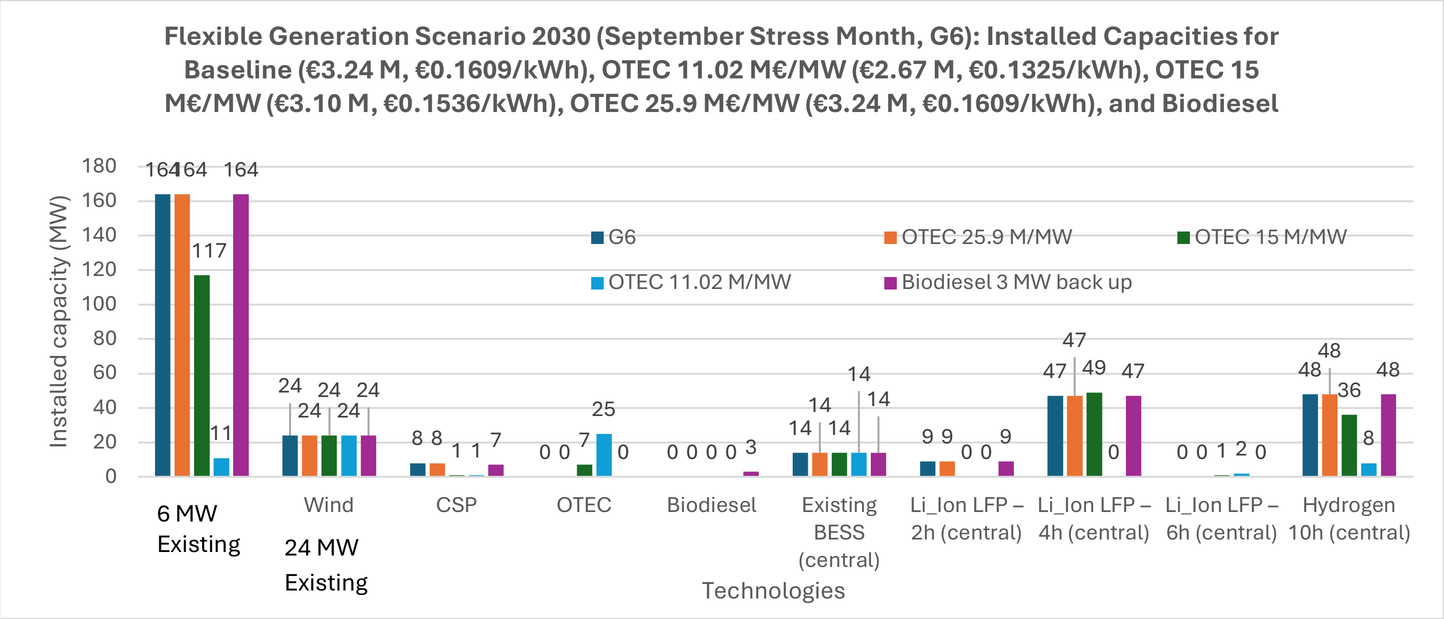

Flexible Generation Scenario 2030 (September Stress Month, G6): Installed Capacities for Baseline (€3.24 M, €0.1609/kWh), OTEC 11.02 M€/MW (€2.67 M, €0.1325/kWh), OTEC 15 M€/MW (€3.10 M, €0.1536/kWh), OTEC 25.9 M€/MW (€3.24 M, €0.1609/kWh), and Biodiesel

Figure 25: Flexible Generation Scenario 2030 (September stress month, G6). Installed capacities of solar, wind, CSP, OTEC, and biodiesel generation are compared for five configurations: (i) baseline without OTEC, (ii) OTEC at 11.02 M$/MW, (iii) OTEC at 15 M$/MW, (iv) OTEC at 25.9 M$/MW, and (v) biodiesel 3 MW backup. The total monthlyized added capacity costs amount to $3.24 million ($0.1609/kWh) for the baseline, $2.67 million ($0.1325/kWh) for OTEC 11.02 M$/MW, $3.10 million ($0.1536/kWh) for OTEC 15 M$/MW, and $3.24 million ($0.1609/kWh) for both OTEC 25.9 M$/MW and biodiesel backup (model results).

Chapter 10: Discussion

This chapter discusses the results of the modelling work in relation to the overall research design and research questions. As outlined in the research framework, the study progressed in several steps. First, the current power system of Bonaire was analysed, and evaluation criteria were developed through stakeholder analysis and literature review. Second, renewable energy options for the island were synthesised (SQ1) and complemented with an assessment of flexibility options, including both demand-side measures and energy storage technologies (SQ2 and SQ3). These insights were used as input scenarios in the linear optimal power flow model of Bonaire to generate reliable and cost-efficient energy system configurations (SQ4). The results of these intervention scenarios are discussed in this chapter and assessed against the key stakeholder criteria (2.3.5).

The discussion in this chapter therefore addresses the central research question: ***How can a fully renewable electricity system be designed for Bonaire that ensures reliability, affordability, sustainability and energy security?***

Each intervention: demand-side management, decentralized storage, biodiesel as a transitional reliability reservoir, CSP with storage, and OTEC, is assessed against these criteria and compared to the base case. In doing so, the discussion not only interprets the technical outcomes of the modelling but also reflects on their broader implications for Bonaire's energy transition, including trade-offs, limitations, and co-benefits. Building on these results, the analysis then turns to the implications for WEB Bonaire, highlighting how flexibility can be integrated into future planning. The chapter also reflects on the limitations of the modelling approach and the thesis. Finally, it outlines the contribution of this study to both local decision-making and the wider academic literature on small island energy transitions.

10.1 Discussion of results compared to the base case and evaluation against criteria

This chapter compares the 2030 base case with a set of intervention scenarios, assessing their impacts on reliability, affordability, energy security, and environmental sustainability. The base case reflects the current energy mix of solar PV, wind, and storage, and includes concentrated solar power (CSP) as part of the solar resource. While CSP is not yet deployed on the island, it is included to represent the same solar potential. For both the base case and each intervention scenario, two annual demand growth assumptions are applied: 3% (G3) and 6% (G6). This serves to validate the growth assumptions and explore whether different demand levels favour system configurations or interventions. Three interventions are analysed, focusing on flexibility options from different perspectives: demand-side measures, supply-side measures, and energy storage. These are evaluated not only in terms of cost and reliability but also with respect to energy security and environmental sustainability, using the stakeholder criteria outlined in Section 2.3.5. By comparing flexibility strategies across these criteria, the analysis goes beyond simple cost optimization and highlights the trade-offs between reliability, economic feasibility, supply security, and environmental responsibility.

The results for September should be interpreted as a stress test for the energy system rather than as a representation of typical annual performance. Since September combines peak electricity demand with relatively low solar and wind generation, it represents one of the most challenging operating conditions for the system. Evaluating scenarios during this month provides insight into how different interventions perform under high-stress situations, particularly in terms of the key criteria. While this approach does not reflect seasonal variations throughout the year, it allows for a robust comparison of system configurations under worst-case conditions. However, yearly and longer-term impacts are considered for each intervention and each criterion.

10.1.1 Reliability

Reliability is measured by the system's ability to consistently meet demand, including during periods of peak stress or low renewable output. A reliable grid provides stable and continuous electricity, quickly restores service during interruptions, and withstands disruptions such as storms or equipment failures without prolonged outages (Energy Reliability and Resilience, n.d.). In this study, reliability is achieved by design as a model constraint, but its quality can be assessed through the diversity and capacity of generation, and the availability of storage systems to maintain supply during stress periods. September is chosen as the stress month, however yearly implications are also considered, particularly during the July–November storm season and potential system stress in other months.

The baseline configuration is dominated by solar PV, supported by wind, CSP, and a combination of battery and hydrogen storage. As demand grows, solar capacity expands significantly, while wind remains constant and CSP increases slightly. This system can meet demand during September, but its heavy reliance on solar power makes it vulnerable during longer periods of low renewable generation, such as during storm season. CSP plays an important stabilizing role by shifting daytime solar production into the evening, reducing immediate pressure on batteries, but there is no firm baseload capacity. This lack of dispatchable generation limits the system's ability to respond to prolonged or unexpected supply shortfalls outside the stress month, particularly during multi-day periods of low renewable output.

Supply-side interventions address this vulnerability by introducing Ocean Thermal Energy Conversion (OTEC) and biodiesel as firm and flexible generation sources. OTEC provides stable baseload capacity, strengthening reliability during extended periods of low solar and wind and reducing dependence on storage. The installed OTEC capacity depends on cost assumptions: at moderate costs, only a modest amount is added, while at lower costs, OTEC plays a much larger role in the generation mix. This diversification reduces solar dependency and improves resilience to weather-related variability and shocks throughout the year. Biodiesel, using existing gensets, is introduced as short-duration backup and is dispatched only during rare peak events under low growth, and not at all under high growth in September. Its presence, however, adds an extra layer of security during unexpected outages or events outside the stress period. The combination of OTEC and biodiesel yields the highest generation diversity among the scenarios, making the system more robust against prolonged stress events, including storms that may affect solar or wind output.

The storage intervention focuses on the addition of decentralized storage while maintaining a similar generation mix to the baseline. Small battery units are installed at the wind park, providing localized buffering of wind production. Although this does not significantly change overall storage capacity, it slightly improves local resilience by supplying power closer to where it is generated. This is valuable during localized faults, such as distribution station outages or road accidents, which can temporarily isolate parts of the network. Given Bonaire's grid is not congested yet and the economies of scale of centralized storage, the impact on overall reliability remains modest at this scale. However, in the longer term, strategically placing decentralized storage near critical loads could complement centralized storage and enhance the system's ability to maintain supply during emergencies.

Demand-side flexibility reduces evening cooling loads and shifts electric vehicle charging to early morning hours, flattening demand peaks and lowering required generation and storage capacity. Under moderate growth, even low levels of participation significantly reduce evening peaks, while higher participation levels further improve reliability without the need for additional generation assets. Under high growth, achieving similar reliability outcomes depends on maintaining high and consistent participation. However, DSM relies on sustained behavioral changes, which can vary seasonally and are less controllable than dispatchable generation or storage during sudden events. While effective during September, its contribution to reliability over the year depends on stable and predictable user behavior, which introduces uncertainty under unexpected stress conditions such as storms or outages.

Across all interventions, generation diversity and storage capacity are the key determinants of reliability. The baseline system's strong dependence on solar makes it more exposed to extended periods of low renewable output. Supply-side interventions offer the most significant reliability improvements by adding firm generation through OTEC and limited backup through biodiesel, reducing vulnerability to solar variability and seasonal risks. Storage interventions provide modest improvements in local resilience, with greater potential if decentralized capacity is expanded strategically. Demand-side flexibility effectively lowers peak pressures under moderate growth but depends on consistent participation, which is less guaranteed under real-world conditions. Over the longer term, ensuring reliable electricity supply requires a balanced combination of firm generation, flexible storage, and targeted demand-side measures. OTEC provides steady baseload, CSP structurally shifts solar to evening peaks, centralized storage remains the backbone of system flexibility, while decentralized storage and DSM can complement these elements by enhancing local resilience and managing demand peaks. Together, these measures build a more robust and reliable energy system capable of withstanding both short-term stress events and year-round variability.

10.1.2 Affordability

Affordability and economic sustainability are central concerns for consumers, regulators, and operators. Consumers prioritize low and stable electricity prices, while regulators focus on fair tariffs and cost recovery to ensure utilities remain financially viable. In the Caribbean Netherlands, the Netherlands Authority for Consumers and Markets (ACM) set electricity tariffs based on total investment and operational costs, ensuring cost recovery while maintaining stable pricing structures. Affordability is therefore assessed through total system costs and their impact on consumer tariffs.

Both capital expenditures (CAPEX) and fixed operation and maintenance costs (FOM) are annualized using a Weighted Average Cost of Capital (WACC) of 8.7%, based on ACM's official value for 2026–2028, and then divided by twelve to obtain monthlyized costs. This ensures that lifetime system costs reflect both upfront investments and ongoing fixed expenses and allows technologies with different lifetimes to be compared fairly within the one-month stress simulation. Costs are assessed using two indicators: total monthly system cost, which reflects the overall economic scale of each scenario, and the cost per kilowatt-hour, which indicates expected tariff impacts. For lifetime comparison, monthlyized costs are extrapolated to 30 years to reflect the technical lifetime of major assets such as solar PV, wind, CSP, OTEC, and hydrogen storage. Lithium-ion batteries are assumed to last 15 years, implying one full replacement during the period. Net present values (NPV) are calculated using the WACC as the discount rate, providing a time-consistent comparison across scenarios.

This approach ensures that different technological mixes and investment structures can be compared on a consistent financial basis, accounting for lifetime and replacement cycles.

It is important to note that the cost analysis is based on the stress month of September, which typically combines the highest annual peak demand with relatively low solar and wind availability. Consequently, the monthlyized costs derived from this period likely overestimate average annual costs, as most other months feature either higher renewable generation or lower demand peaks. For instance, while November exhibits even lower renewable output, months with stronger renewable availability would generally lead to lower operational costs per kilowatt-hour. Despite this, September provides a robust upper-bound estimate: the capacities required to meet demand during this month are also necessary for ensuring reliability throughout most of the year. This makes it a suitable and conservative basis for comparing scenarios.

In the baseline configuration, monthlyized system costs are approximately \$2.7 million (\$0.154/kWh) under the G3 growth scenario. These costs reflect high solar capacity combined with significant storage to meet evening peaks. While effective in September, this structure could result in higher costs during months with lower renewable output or higher demand, due to increased reliance on storage cycling or backup resources. Demand-side flexibility significantly reduces capacity requirements and costs. Under G3, increasing DSM participation lowers monthlyized costs from \$2.71 million in the baseline to \$2.11 million under high flexibility. By shifting and reducing evening loads, DSM enables the system to operate with less solar and storage capacity. However, this relies on consistent user participation, which may vary seasonally and is less controllable during unexpected events, potentially affecting cost performance in other months. The decentralized storage intervention leaves system costs almost unchanged. A small 2 MW battery at the wind park improves local operational flexibility but does not affect overall costs due to economies of scale favoring centralized storage. While cost-neutral in the short term, decentralized storage could reduce costs over time if it avoids future grid reinforcements.

The supply-side intervention, adding OTEC and biodiesel, highlights a clear cost–reliability trade-off. At low OTEC costs, total system costs fall substantially because firm baseload generation reduces solar and storage needs. At moderate costs, installed capacity is smaller but still improves stability, with costs near baseline levels. At high OTEC costs, no OTEC is installed, and the system reverts to the baseline solar–storage mix. Biodiesel adds limited backup capacity used only a few hours annually, with negligible impact on total costs but important for reliability. Its use is limited to approximately 213 hours annually, with an estimated cost of USD 62,622 per year, reflecting the premium price of biofuel. Though economically minor, it provides strategic reliability during critical periods without depending on diesel as a primary source. These results show that OTEC's cost-effectiveness depends strongly on technology costs: low-cost OTEC improves both reliability and affordability, whereas high-cost OTEC introduces a cost–resilience trade-off.

Table 13 summarizes the monthlyized costs and 30-year NPV values for the G3 (3% growth) scenarios. Lifetime NPVs are calculated by multiplying monthly costs by twelve and discounting over 30 years at 8.7% WACC; battery replacements are implicitly included. The results for the high growth (6%) scenario show similar patterns and are presented in Appendix I, where a comparable cost table is included. Higher demand raises total costs, but the relative differences between interventions remain consistent, confirming the robustness of the trade-offs.

Table 13 Monthlyized and Lifetime System Costs under 3% Demand Growth (G3)
This table presents the monthlyized system costs, levelized costs per kilowatt-hour, and lifetime Net Present Value (NPV) over 30 years for all intervention scenarios under the low demand growth (G3) pathway. Costs are based on the September stress month and include both CAPEX and fixed O&M, annualized using a WACC of 8.7%

Scenario	Monthlyized Cost	Cost/KWh	Annual Cost	30-Year NPV
Baseline	2.71 M $	0.1541 $/kWh	32.5 M $	348 M $
DSM – Low	2.50 M $	0.1498 $/kWh	30.0 M $	321 M $
DSM – Medium	2.34 M $	0.1461 $/kWh	28.1 M $	301 M $
DSM – High	2.11 M $	0.1406 $/kWh	25.3 M $	271 M $
Decentralized Storage	2.70 M $	0.1536 $/kWh	32.4 M $	347 M $
OTEC (11.02 M$/MW)	2.28 M $	0.1299 $/kWh	27.4 M $	293 M $
OTEC (15 M$/MW)	2.61 M $	0.1485 $/kWh	31.3 M $	335 M $
OTEC (25.9 M$/MW)	2.71 M $	0.1541 $/kWh	32.5 M $	348 M $
Biodiesel Backup	2.70 M $	0.1534 $/kWh	32.4 M $	347 M $

When compared to current costs, the transition scenarios offer significant savings. In January 2024, Bonaire's total production price was USD 0.3386/kWh, with USD 0.1976/kWh attributable to diesel fuel alone. In contrast, all 2030 scenarios under 3% growth result in total system costs between USD 0.13 and 0.15/kWh, lower than the diesel fuel cost alone. This illustrates that replacing diesel with a mix of renewables, storage, and flexibility can substantially reduce electricity costs while improving reliability and resilience. Over the long term, affordability depends on balancing reliability and cost. Low-cost OTEC improves both, DSM can deliver savings under stable participation, and decentralized storage has future potential as the grid evolves. A balanced mix of supply diversification, flexible demand, and efficient storage offers the most economically sustainable pathway, minimizing lifetime system costs while maintaining reliable supply.

10.1.3 Energy Security

Energy security is fundamentally about ensuring that energy remains available, affordable, and resilient to both external shocks and internal disruptions over the long term. It involves securing reliable access to energy resources while minimizing exposure to geopolitical risks, supply chain disruptions, and price volatility. Empirical evidence has shown that increasing renewable energy use lowers long-term energy security risks by reducing exposure to fossil fuel price shocks and geopolitical disruptions. At the same time, rapid transitions can introduce short-term vulnerabilities, including intermittency challenges, infrastructure bottlenecks, and policy uncertainty, which highlights the importance of designing diversified and resilient energy systems (Wang & Tian, 2025).

In the current diesel-based system, Bonaire's energy security is weakened by its near-total reliance on imported fossil fuels, leaving it vulnerable to global oil price fluctuations, supply interruptions, and geopolitical instability. By 2030, all modeled scenarios eliminate diesel as a primary energy source, relying almost entirely on locally available renewable resources. This represents a fundamental shift, as energy security no longer depends on continuous imports but on the robustness and diversity of the local energy system. The baseline scenario relies almost exclusively on solar PV and wind, supported by battery and hydrogen storage. While this eliminates fuel imports, it introduces a new dependency on weather conditions and storage performance. Prolonged periods of low renewable availability, such as during storms or extended cloudy weeks, could challenge system resilience if not complemented by dispatchable resources. The limited diversity of the generation mix makes the system more vulnerable to climate-related variability, particularly during the hurricane season.

The supply-side intervention, introducing Ocean Thermal Energy Conversion (OTEC) and biodiesel, enhances energy security by diversifying the generation mix. OTEC provides local, dispatchable baseload capacity that reduces exposure to solar and wind variability and operates independently of imported fuels once installed. Biodiesel offers a small 3 MW emergency backup, used for approximately 213 hours per year. While biodiesel requires imports, this represents a limited and manageable supply requirement, typically secured through long-term contracts rather than continuous deliveries. Among all interventions, this scenario provides the greatest diversification of supply, improving resilience against climatic events, prolonged renewable shortfalls, and geopolitical supply risks.

The decentralized storage intervention contributes modestly to energy security by improving local resilience. Locating small storage units at strategic points enables the system to maintain supply to critical loads during distribution faults or localized outages. However, because Bonaire's grid is compact and centralized storage remains more cost-efficient, the impact on overall energy security is limited at this stage. Its strategic value may increase in the future if network congestion grows or extreme weather events affect transmission infrastructure.

Demand-side flexibility supports energy security indirectly by flattening peak demand and reducing the amount of imported infrastructure needed to meet peak loads. This lowers exposure to global supply chains for solar panels, wind turbines, and batteries. However, its effectiveness depends on sustained household and business participation. Over time, participation may decline as living standards rise or electricity prices fall, reducing the incentive to shift demand. Seasonal variations and behavioral fatigue could further weaken its reliability as a structural energy security measure. Without formal contractual frameworks demand-side management remains a complementary rather than foundational strategy for long-term energy security.

Across all scenarios, several patterns emerge. High levels of local renewable generation strengthen energy security by reducing dependence on imported fuels and shielding the system from global fuel market volatility. Diversification through OTEC, CSP, storage, and demand measures enhances resilience against climatic variability and supply shocks. While demand-side management and decentralized storage provide useful support functions, dispatchable local generation and limited emergency biodiesel backup offer the most robust protection against prolonged or extreme events. Overall, the supply-side intervention with OTEC and limited biodiesel backup offers the strongest long-term energy security, combining local dispatchable generation, fuel import independence, and diversification. The baseline system, while renewable, remains vulnerable to climatic fluctuations due to its heavy reliance on solar and wind. Demand-side measures and decentralized storage add flexibility but depend on behavioral or infrastructural factors that may not be guaranteed over the long term. Ensuring secure and reliable energy supply on Bonaire will therefore require combining renewable expansion with strategic diversification and targeted resilience measures.

10.1.4 Environmental sustainability

Environmental sustainability is a core pillar of Bonaire's energy transition. It encompasses both global objectives—such as reducing greenhouse gas emissions—and local priorities, including the protection of ecosystems, biodiversity, and the island's limited land resources. These considerations are particularly critical in Bonaire, where land is scarce and subject to competing uses such as conservation, tourism, housing, and agriculture. The transition to a fully renewable energy system must therefore balance decarbonization objectives with spatial and ecological constraints to ensure that the island's natural environment is preserved while meeting future energy needs.

The assessment focuses on two primary dimensions: land use and air pollution, complemented by qualitative consideration of other environmental impacts such as water use, material intensity, and end-of-life management. Land use is especially relevant because large-scale renewable deployment requires significant space, which is limited on the island. Emissions are evaluated in terms of indicative lifecycle intensities to reflect not only operational performance but also embedded emissions from construction and manufacturing. While a full lifecycle assessment is beyond the scope of this thesis, the discussion highlights the most important trade-offs for Bonaire's transition context.

To provide a clear overview, Table 14 summarizes the key land-use assumptions and indicative lifecycle emissions for each scenario under both the low (G3) and high (G6) growth pathways. The table includes installed solar PV and wind capacities for each scenario, land-use requirements calculated using global median values for solar (1.4 ha/MW) and local spacing assumptions for wind (turbines of 0.9 MW spaced approximately 200 m apart), and indicative emission intensities based on literature values. OTEC is considered land neutral, as most of its infrastructure is offshore, while biodiesel is assumed to use existing genset locations, with upstream land use occurring outside Bonaire.

Land availability and sitting play a decisive role in determining environmental impacts. On Bonaire, suitable land for solar development is concentrated primarily in the island's east, characterized by windswept Caribbean savannah with bare soil and low scrub vegetation. This area avoids key ecological zones such as forests, high scrub, mangroves, salt ponds, built-up areas, and agricultural land (see Appendix J). Concentrating solar development in these areas minimizes conflicts with conservation, urban and tourism. Wind development is already situated along the eastern coast, where twelve 0.9 MW turbines are spaced approximately 200 m apart along a 2.2 km coastal corridor. Although the direct footprint of each turbine is small, the spacing required between them creates a large effective land area that cannot easily be used for other infrastructure, constraining further expansion along this corridor.

OTEC installations are located offshore and are therefore considered neutral, requiring only limited coastal space for pumps and heat exchangers. Biodiesel uses existing generator sites and thus has no additional land requirement on the island, though upstream impacts in exporting regions remain relevant. The environmental implications of DSM and decentralized storage interventions are indirect: DSM reduces total required PV and storage capacity by flattening peaks, thereby lowering the physical infrastructure and material intensity of the system. Decentralized storage can support local self-consumption and reduce curtailment but increases the number of small battery units, raising material and lifecycle impacts compared to centralized storage, which is generally more resource efficient.

Table 14: Land use and indicative lifecycle emissions for each scenario under G3 and G6
The table summarizes the installed PV and wind capacities, calculated land-use requirements, and indicative lifecycle emissions for each scenario. Land use for PV is based on 1.4 ha/MW. Wind spacing assumes 200 m per 0.9 MW turbine, representing the typical configuration along Bonaire's eastern coast.

Scenario / Intervention	**Solar PV (MW) G3 / G6**	**Wind (MW) (G3=G6)**	**PV land use (km^2) G3 / G6 (1.4 ha/MW)**	**Wind corridor (km)**	**Indicative lifecycle emissions ($g\ CO_2/kWh$)**	**Key environmental characteristics**
Baseline / Decentralized storage / OTEC 25.9 / Biodiesel backup	138 / 164	24	1.932 / 2.296	~5.4	PV 32–82; wind 10–12; biodiesel ~165 (backup only)	Fully renewable; largest PV footprint; fixed coastal wind corridor; biodiesel uses existing gensets and runs ~213 h/yr (minor emissions); high storage material intensity
DSM – Low	128 / 155	24	1.792 / 2.170	~5.4	Same as baseline	Moderate PV land savings via load reduction/shift; depends on participation consistency
DSM – Medium	121 / 146	24	1.694 / 2.044	~5.4	Same as baseline	Clear PV land reduction; lower material imports for PV and storage
DSM – High	110 / 110	24	1.540 / 1.540	~5.4	Same as baseline	Largest PV land and material reduction; environmental benefit contingent on sustained high participation
OTEC (11 M$/MW)	11 / 11	24	0.154 / 0.154	~5.4	PV/wind low; OTEC low embedded; biodiesel ~0	Strongest land-use reduction by shifting generation offshore; manage marine ecological risks (intakes/discharges, siting)
OTEC (15 M$/MW)	101 / 117	24	1.414 / 1.638	~5.4	Similar to baseline (lower PV share)	Offshore generation reduces PV area versus baseline; marine impacts require careful design/siting

Emissions during operation are largely determined by the generation mix. Wind, solar PV, CSP, and OTEC produce no direct emissions during operation, with lifecycle intensities dominated by manufacturing and construction. Wind has the lowest lifecycle emissions, typically around 10–12 g CO_2/kWh. PV follows with 32–82 g CO_2/kWh, reflecting energy-intensive silicon purification. CSP is slightly higher (36–91 g CO_2/kWh) due to its molten salts and steel infrastructure but remains far below fossil generation. OTEC emissions stem mainly from the production and installation of pipes, with operational emissions being negligible. Biodiesel, by contrast, emits directly during combustion, averaging about 165 g CO_2/kWh, depending on the feedstock. Although it is often considered carbon neutral if sourced from waste streams, its upstream impacts can be substantial if feedstock comes from dedicated energy crops.

Across scenarios, these characteristics translate into clear differences in environmental performance. The baseline scenarios rely on high PV and wind capacities, which require moderate but manageable land areas, primarily in the east, and generate low lifecycle emissions. DSM interventions reduce both land use and emissions indirectly by lowering the total required capacity. Decentralized storage does not significantly change land use but increases the number of units deployed. The OTEC scenarios stand out for their land neutrality and very low emissions, offering a structurally different environmental profile by shifting generation offshore. Biodiesel backup is land neutral and has a negligible annual operating duration (around 213 hours), so its total emissions are minor, though securing sustainable feedstock supply remains important for long-term sustainability.

The overall land requirements are modest relative to Bonaire's total area. In the base case 6% growth, solar PV occupies roughly 2.3 km^2 and wind around 5.4 km spacing. These installations are sited away from sensitive ecosystems and urban areas, minimizing conflicts with other land uses. Figure 26 illustrates the spatial distribution of PV and wind development under the baseline scenario. This demonstrates that the island's renewable energy targets can be met without encroaching on critical ecosystems, if development is carefully planned and concentrated in suitable areas.

Environmental sustainability assessments also consider other dimensions such as water use, biodiversity, and end-of-life management. CSP is the most water-intensive technology, while PV requires water mainly for cleaning. Wind and OTEC use negligible freshwater. Biodiversity impacts differ by technology: wind turbines can affect birds and bats, PV and CSP may alter ground habitats, and OTEC may impact marine ecosystems through intake and discharge flows, though careful design can mitigate these effects. Lifecycle and waste issues are most pressing for PV panels and batteries, which contain heavy metals and require effective recycling strategies. Centralized battery systems are likely to be more manageable in this regard than numerous small, decentralized units.

In summary, all scenarios achieve substantial reductions in emissions compared to the current fossil-based system. Land use requirements are moderate and can be accommodated through strategic siting, particularly in the east of the island. The OTEC scenarios offer the lowest land use and emissions, but at higher capital cost. DSM is environmentally beneficial by lowering system size, while decentralized storage has neutral to slightly negative lifecycle impacts compared to centralized solutions. Biodiesel remains a useful transitional option with limited use. These findings indicate that Bonaire's energy transition can be achieved in an environmentally sustainable manner if technology deployment is carefully planned and integrated with spatial and ecological considerations.

Figure 26. Spatial allocation of solar PV and wind development under the baseline 2030 scenario
The map illustrates the indicative spatial allocation of renewable energy infrastructure on Bonaire under the baseline 2030 6% growth scenario. For solar approximately 158 MW will be added, requiring around 2.3 km^2 of land, primarily located in the eastern part of the island on bare soil and low scrub Caribbean savannah, where ecological sensitivity is low. Wind capacity totals approximately 5.4 MW, of which 2.2 MW is already installed along the Morotin coastal corridor. New turbines follow the same spacing pattern of roughly 200 m along the eastern coast, expanding this corridor while avoiding urban areas and sensitive ecological zones. Environmentally sensitive areas such as forests, mangroves, salt ponds, agricultural land, and urban zones are excluded from development. This spatial configuration minimizes land-use conflicts while accommodating the required capacities for the baseline scenario (Verweij, 2024) with own elaboration.

10.1.5 Conclusion

The results reveal clear trade-offs between interventions when evaluated against reliability, affordability, energy security, and environmental sustainability. No single intervention performs best across all criteria; rather, each offers distinct advantages and limitations that reflect its role within the system. Table 15 summarizes these trade-offs and key insights for each intervention across the four criteria.

Supply-side diversification through OTEC and limited biodiesel backup provides the strongest gains in reliability and energy security by adding firm, dispatchable capacity and reducing dependence on weather-driven generation. Although OTEC increases capital costs, its ability to enhance system stability and reduce exposure to climatic variability may justify paying a premium for long-term resilience, particularly for an island system with limited interconnection options. DSM delivers notable affordability and environmental benefits by reducing system size, but its reliability and security contributions hinge on sustained behavioral participation. Decentralized storage improves local resilience and supports self-consumption, but its system-wide impact is modest and lifecycle impacts may increase compared to centralized solutions. The baseline configuration achieves full renewable supply but remains most exposed to climatic variability due to its heavy reliance on solar and wind.

These trade-offs highlight the need for a balanced portfolio approach, rather than reliance on any single measure. Combining firm generation (OTEC and limited biodiesel), centralized storage, and targeted DSM offers the most robust pathway: maintaining reliability, enhancing affordability through system optimization, strengthening long-term energy security, and achieving environmental goals through careful siting and technology selection. In this context, strategic investments in more expensive but resilient technologies like OTEC can be economically rational when considering the full range of system benefits over the long term.

Table 15: Summary of key impacts and trade-offs of interventions across evaluation criteria

INTERVENTION	RELIABILITY	AFFORDABILITY	ENERGY SECURITY	ENVIRONMENTAL SUSTAINABILITY
BASELINE	High solar dependence; vulnerable to prolonged low renewable output	Moderate cost (0.15 $/kWh); driven by large PV + storage	Fully renewable; exposed to climatic variability	Moderate PV land use (~2.3 km^2); fixed wind corridor (~5.4 km); low emissions
DSM (LOW–HIGH)	Reduces peak load; effectiveness depends on participation	Significant cost reduction under medium–high participation	Reduces imported equipment needs; depends on stable user behaviour	Lowers PV and storage capacity requirements; reduces land use and material intensity
DECENTRALIZED STORAGE	Improves local resilience; limited system impact	Cost neutral at present (centralized more efficient)	Supports critical loads during local faults; modest contribution overall	No major land change; more small units increase lifecycle material intensity
OTEC (LOW–HIGH COST)	Provides firm baseload; strongest reliability improvement	Low cost improves both reliability and cost; high cost creates trade-off	Diversifies supply; local dispatchable generation; independent of imports	Land neutral; offshore infrastructure; low embedded emissions
BIODIESEL BACKUP	Provides emergency backup (~213 h/year)	Negligible cost impact	Limited, contract-based imports; enhances resilience during rare events	Land neutral (uses existing gensets); minor total emissions due to limited use

10.2 Strategic Implications for WEB Bonaire

The modelling results and stakeholder surveys together provide a clear set of strategic implications for WEB Bonaire's planning and operations in the period up to 2030. The analysis demonstrates that achieving a reliable, affordable, secure, and environmentally sustainable electricity system depends on a balanced combination of supply- and demand-side measures, supported by appropriate institutional arrangements and investment strategies. While technical feasibility has been demonstrated across all scenarios, the pathways differ significantly in terms of costs, risks, and long-term benefits. Translating these findings into actionable planning requires prioritizing flexibility, diversification, and targeted investments.

A first and immediate priority is to treat demand-side management (DSM) as a structural component of the electricity system rather than an optional add-on. The modelling shows that DSM can substantially reduce required solar PV and storage capacity while maintaining reliability. Under moderate growth, even low to medium participation rates lower peak loads and shift demand into periods of high solar availability, reducing total system costs and land requirements. The household and large-customer surveys confirm that the willingness to adopt flexible behaviours is already widespread, even in the absence of time-of-use tariffs. This creates a strong foundation for structured DSM and demand response programs. To secure the benefits over time, DSM must be formalized through clear price signals, targeted communication, and possibly contractual arrangements. Relying solely on voluntary participation risks erosion of effectiveness as living standards rise or electricity prices decline.

Second, biodiesel should be maintained as a transitional reliability hedge. Re-using the existing diesel gensets with biodiesel provides a low-cost mechanism to cover rare but severe periods of low renewable output, especially during the early phases of the transition. Its use is limited to roughly 213 hours annually, making it a marginal cost item while offering strategic insurance against extreme events. This role aligns well with energy security objectives, as biodiesel imports can be secured through long-term contracts rather than continuous supply chains. While not a long-term solution due to its emissions and import dependence, biodiesel is an important bridge resource that allows rapid decarbonization without compromising reliability.

Third, concentrated solar power (CSP) emerges in the modelling as a valuable structural resource. With ten hours of thermal storage, CSP shifts solar generation into the evening peak, reducing reliance on batteries and biodiesel and stabilizing the system during daily stress periods. Although CSP is land intensive and not currently deployed on Bonaire, its role in the 2030 scenario highlights its potential contribution to reliability and reduced storage dependency. Integrating CSP strategically into the generation mix can therefore support both operational stability and long-term cost control.

Ocean Thermal Energy Conversion (OTEC) stands out as a potential anchor technology for the post-2030 energy system. As a local, dispatchable baseload resource, OTEC strengthens system reliability and energy security while operating independently of imported fuels. It also has a land-neutral footprint and co-produces freshwater, which aligns with Bonaire's broader sustainability objectives. The main trade-off lies in cost: at low to moderate cost assumptions, OTEC significantly reduces reliance on solar and storage, lowering long-term system costs, while at higher costs, it represents a strategic premium for enhanced resilience and security. In terms of planning, WEB Bonaire should consider OTEC as a long-term investment option, with careful attention to technological maturity, cost trends, and environmental safeguards.

Decentralized storage plays a complementary but more modest role. In the modelled scenarios, small battery systems at the wind park improve local resilience and buffering but have limited impact on overall system performance due to economies of scale favoring centralized storage. Nevertheless, decentralized storage may become more relevant over time if network congestion grows or critical loads require localized backup, for example during extreme weather events.

Large commercial consumers also represent a critical strategic actor. Survey results show widespread adoption of PV and efficiency measures but a lack of structured participation in DSM. Without coordinated engagement, self-generation could flatten individual bills without contributing to system-wide peak reduction. WEB Bonaire should therefore develop targeted DSM contracts and financial incentives tailored to large consumers, particularly hotels and commercial facilities whose loads often coincide with system peaks. Integrating these actors into DSM frameworks will be essential for achieving the projected cost and capacity savings.

Finally, sectoral coordination adds further opportunities. The water sector, which relies on steady operation of reverse osmosis plants, can offer limited but valuable flexibility by adjusting storage set-points to avoid peak periods. Similarly, managed EV charging has the potential to reduce evening peak demand significantly if appropriate control strategies are adopted. These measures underline the importance of cross-sectoral planning to maximize flexibility resources.

Taken together, these strategic priorities reflect the trade-offs identified across the four evaluation criteria. DSM and CSP provide cost-effective mechanisms to balance demand and supply, lower land requirements, and reduce dependence on imported infrastructure. Biodiesel offers transitional reliability at low cost, while OTEC represents a more expensive but strategically valuable investment in baseload capacity and energy security. Decentralized storage and sectoral flexibility provide additional resilience, particularly for localized disruptions. For WEB Bonaire, the most robust pathway combines immediate DSM implementation, transitional biodiesel use, CSP deployment for structural flexibility, and preparation for OTEC as a long-term anchor resource. This balanced strategy allows the island to achieve reliability, affordability, energy security, and environmental sustainability simultaneously, while managing costs and risks over time.

10.3 Research and model limitations

While the modelling presented in this thesis provides valuable insights into pathways for a fully renewable electricity system on Bonaire, several limitations should be acknowledged. These relate to the scope of the analysis, the availability and quality of data, and structural uncertainties regarding implementation and future developments.

The first limitation concerns the temporal scope of the modelling. The simulations were based on one representative stress month, September, to test system configurations under peak demand and low renewable availability. This approach provides a robust upper-bound assessment but does not capture seasonal and interannual variations in demand, solar radiation, and wind resources. Electricity demand on Bonaire varies throughout the year due to tourism cycles and weather patterns, while renewable availability is subject to seasonal and stochastic fluctuations. Incorporating full-year and multi-year datasets in future work would allow a more comprehensive evaluation of reliability and cost performance over time, including the effects of extreme events such as multi-day wind lulls or extended cloudy periods.

A second limitation relates to data quality and granularity. Renewable resource data were interpolated from available measurements and literature-based assumptions. High-resolution, long-term resource measurements would improve the robustness of reliability assessments, particularly for wind and solar variability. Similarly, the representation of grid infrastructure was simplified. Detailed grid topology, operational constraints, and protection schemes were not included, which may affect the real-world feasibility of system operation under high renewable penetration.

A third limitation concerns cost assumptions, particularly for emerging technologies such as OTEC and CSP. While cost inputs for solar and wind are based on local project data, there is substantial variability in the literature across different geographic and technological contexts. OTEC and CSP remain at early stages of deployment, and their actual costs on Bonaire could diverge significantly from the values assumed in the model. Results should therefore be interpreted as indicative scenarios rather than precise forecasts.

A fourth limitation involves the representation of demand-side behavior. Participation in DSM was modelled deterministically, using survey data on willingness to shift loads under time-of-use pricing. The analysis focused on the potential contribution of DSM, rather than on its practical implementation. Policy design, tariff structures, and regulatory frameworks were not explored in detail. Sector coverage was also limited, with less attention from large customers such as those in the hospitality sector. The model does not account for behavioral inertia, rebound effects, or long-term participation trends, and it does not incorporate explicit price elasticities. As a result, real-world DSM performance may differ significantly from model assumptions depending on how programs are designed and how customers respond over time.

A fifth limitation concerns the treatment of storage technologies. Round-trip efficiencies and costs were included, but important characteristics such as degradation, cycling limits, and long-term performance were not modelled explicitly. This may lead to an underestimation of long-term costs in storage-heavy scenarios. Operational constraints such as state-of-charge management, ramping limitations, or grid integration challenges were also not considered in detail.

A sixth limitation relates to the operational modelling framework. The use of linear optimal power flow with hourly resolution is appropriate for high-level planning, but it abstracts from important operational issues such as sub-hourly variability, frequency control, voltage stability, and fault ride-through capabilities. These operational aspects are likely to become increasingly important as the share of variable renewables grows.

Beyond the modelling itself, there are broader research limitations. Institutional, policy, and financing mechanisms were not explicitly modelled, despite their critical role in shaping implementation timelines, investment decisions, and public acceptance. Land-use conflicts, permitting processes, and supply chain constraints were considered qualitatively but not quantified. DSM policy instruments were not developed or evaluated in detail, as the focus was on technical potential rather than program design. Although the analysis was tailored to Bonaire, applying the results to other islands would require careful adaptation to local resource, policy, and institutional conditions.

The timeline of the research also introduced limitations. Because the study took place over an extended period, some assumptions and input data reflect earlier stages rather than the most recent technological and policy developments. This temporal gap may affect the accuracy of cost projections and technology characterizations.

In summary, the modelling framework provides a strong foundation for exploring renewable energy pathways, but future research should extend the temporal scope of the analysis, incorporate more detailed behavioral and operational dynamics, and address institutional, policy, and uncertainty dimensions to support more robust decision-making.

10.4 Contribution of research

This thesis makes contributions at both the applied and academic levels. The following sections outline the practical relevance for WEB Bonaire and policymakers, as well as the broader academic insights for the study of energy transitions in Small Island Developing States (SIDS).

10.4.1 Contribution for WEB Bonaire and policymakers

This thesis provides the first integrated assessment of how Bonaire can achieve a fully renewable electricity system by 2030, considering both technology options and demand-side flexibility. Until now, most energy planning on the island has concentrated on scaling up solar and wind generation supported by batteries, without fully exploring the potential role of demand-side management. The results show that DSM, through household cooling shifts and controlled EV charging, can significantly lower system costs while maintaining reliability. The household survey confirmed a clear willingness among residents to adapt their behavior, indicating that DSM is both technically feasible and socially acceptable in the Bonairean context. The study also identifies new technological options that are relevant for future planning. Ocean Thermal Energy Conversion (OTEC) is highlighted as a long-term cornerstone for reliability and energy security, with the additional benefit of freshwater production. Concentrated Solar Power (CSP) with integrated storage emerges as a structural solution for covering evening demand and reducing reliance on batteries. Biodiesel is positioned as a transitional backup resource, providing reliability during the shift to a renewable system until CSP and OTEC are sufficiently scaled.

While the analysis focuses on the potential and system impacts of DSM rather than detailed policy or tariff design, it provides a solid evidence base for developing future DSM implementation strategies. Beyond technology choices, the energy system model developed in this research can serve as a decision-support tool for WEB Bonaire and policymakers. It allows them to explore future scenarios, assess investment strategies, and evaluate trade-offs between cost, reliability, energy security, and environmental sustainability. Because the model is grounded in real demand data and local cost assumptions, the results are directly relevant to ongoing policy discussions and investment planning. The scenarios also provide a strategic baseline that can be updated as new data, technologies, and policy measures become available.

10.4.2 Contribution to academic knowledge

At the academic level, this thesis contributes to the growing literature on energy transitions in small island developing states. Unlike many techno-economic optimization studies that focus solely on least-cost outcomes, this research applies to a multi-criteria framework that reflects the policy realities of islands, where reliability, energy security, environmental sustainability, and social acceptance are equally important. By integrating empirical survey data on household flexibility with technical energy system modelling, the study connects social and technical perspectives in a way that is rarely applied in small island contexts. This mixed-methods approach highlights both the potential and the limitations of behavioral flexibility, showing how willingness to adapt can reshape system design, while also recognizing uncertainties around actual price responsiveness under time-of-use tariffs. The results also offer comparative insights into the broader literature on island energy transitions. Previous studies from places such as Aruba, Hawaii, and the Canary Islands have focused primarily on technology expansion pathways. This study adds to that debate by demonstrating how DSM and OTEC can shift the balance in small, isolated grids, reducing the need for extreme levels of PV and storage oversizing. The explicit consideration of transitional strategies, in which biodiesel serves as a short-term backup until CSP and OTEC reach maturity, adds nuance to the academic discussion. It moves beyond idealized end-state visions of fully renewable systems and points to a more realistic phased pathway for small islands.

Chapter 11: Conclusion and outlook

This thesis set out to answer the central research question: ***How can a fully renewable electricity system be designed for Bonaire that ensures reliability, affordability, sustainability, and energy security?***

To address this question, the research combined a techno-economic power system model with empirical survey data and a multi-criteria evaluation framework informed by stakeholder priorities. The study explored different renewable generation and flexibility pathways for the year 2030, focusing on the interactions between renewable technologies, demand-side measures, storage systems, and transitional backup options. The analysis was structured through four sub-questions, each addressing a different component of Bonaire's energy transition. This chapter revisits these sub-questions, draws together the key findings, and reflects on their broader implications for Bonaire's energy planning and for academic debates on small island energy transitions. The chapter concludes with recommendations for policy, utilities, and future research.

11.1 Research Questions Revisited

This section formulates answers to each sub question individually and closes by answering the main research question.

11.1.1 Renewable Energy Options

The first sub question aimed to identify feasible renewable energy technologies while minimizing environmental impact: *What renewable energy sources are technically feasible for Bonaire's electricity system, considering environmental sustainability?*

The assessment confirmed that wind and solar photovoltaics form the technical and economic backbone of Bonaire's energy transition. The island benefits from strong and consistent trade winds and high solar irradiation throughout the year. Existing installations, including the Morotin Wind Park and Sorobon turbine, already perform above European benchmarks. Expanding onshore wind capacity to 24 MW would fully exploit the available wind resource along the eastern coastline. Solar PV offers the lowest-cost daytime generation and can be deployed efficiently on the island's eastern savannah, where bare soil and low scrub vegetation minimize conflicts with ecological and urban land uses. Complementary dispatchable technologies are required to address the variability of wind and solar. Concentrated Solar Power (CSP) with integrated thermal storage can shift solar generation into the evening hours, reducing reliance on short-duration batteries. Biodiesel, using the island's existing gensets, provides transitional backup during rare stress events. Ocean Thermal Energy Conversion (OTEC) represents a longer-term strategic option due to Bonaire's steep offshore bathymetry and strong thermal gradients, offering firm baseload output and freshwater co-production once deployed.

The most resilient pathway combines these technologies: wind and solar as the variable backbone, CSP for structural evening coverage, biodiesel as transitional backup, and OTEC as long-term baseload. This diversified mix addresses both reliability and energy security while minimizing dependence on imported fuels.

11.1.2 Demand-Side Flexibility

The second sub question aimed to identify the potential willingness of demand flexibility on Bonaire: *What is the potential of demand-side flexibility in Bonaire's electricity system, based on consumer load patterns and willingness to adapt?*

The household survey conducted in 2025 revealed a strong basis for demand flexibility. Forty-two percent of households indicated that they would voluntarily shift electricity use, and an additional 26 percent would do so if prompted. Efficiency measures such as LEDs and inverter air conditioners are already common, although shading, insulation, and sensor-based controls remain underutilized. Households expressed willingness to shift appliance use away from peak hours, especially between 14:30–16:30 and 19:30–21:30, toward the midday solar window and overnight periods. Pre-cooling strategies and moderate temperature adjustments offer additional potential to reduce evening peaks driven by air conditioning. Large customers, including hotels and commercial sites, show similar patterns. Survey results confirmed widespread adoption of basic efficiency measures and strong interest in self-generation. By aligning operational schedules with off-peak periods (22:00–14:00) and using storage or vehicle-to-grid systems to cover evening loads, these sites can make a substantial contribution to demand-side flexibility. Although the water sector has limited daily cycling flexibility due to reverse-osmosis constraints, adjusted storage setpoints allow modest peak reduction. The mobility sector presents both risks and opportunities: unmanaged EV charging could exacerbate evening peaks, but managed charging and V2G could instead support flexibility.

Overall, Bonaire has both technical and behavioral potential to implement DSM and DR programs that flatten peaks and align demand with renewable generation.

11.1.3 Storage Options

The third sub-question aimed to identify feasible storage technologies and strategic configurations: *What energy storage solutions are suitable for Bonaire's electricity system, considering centralized and decentralized applications as well as the required storage duration and capacity?*

The analysis found that most storage technologies are technically feasible, but scale and geography matter. Pumped storage hydropower and compressed air energy storage were excluded due to the island's lack of suitable topography and geology. Lithium-ion batteries remain the most flexible short- to medium-duration option, already deployed on the island to support grid stability. Flow batteries, sodium-based chemistries, and hydrogen storage offer potential for longer-duration flexibility, though cost and scale considerations are critical. A key trade-off exists between centralized and decentralized storage. Centralized systems benefit from economies of scale and are more cost-effective for bulk energy shifting and peak coverage. Decentralized systems, although costlier per kilowatt-hour, offer localized resilience and can relieve stress in specific parts of the distribution grid. For Bonaire, the optimal strategy is a hybrid configuration: centralized systems for island-wide balancing complemented by targeted decentralized units at critical nodes.

11.1.4 Cost-Optimal Configurations

The last sub question aimed to identify reliable cost-efficient energy systems using insights of previous analysis as input for the scenario modelling: *What is the cost-optimal electricity mix for Bonaire that integrates renewable energy sources and flexibility options to ensure reliability?*

The scenario modelling explores different technology configurations to identify cost-optimal electricity mixes for Bonaire under 3% (G3) and 6% (G6) demand growth for different intervention scenarios. In all scenarios, solar PV and onshore wind form the backbone of electricity generation, complemented by CSP with integrated thermal storage to provide evening dispatchable capacity. System flexibility is mainly delivered through a combination of lithium-ion batteries for daily balancing and hydrogen storage for longer-duration backup, alongside the existing short-duration BESS. Increasing demand-side management participation reduces the required capacities of PV, lithium-ion, and hydrogen storage, since part of the balancing is achieved through flexible demand rather than additional infrastructure. Decentralizing storage shifts its location within the system but does not significantly affect total capacity, with hydrogen remaining a centralized option due to scale advantages. Biodiesel scenarios introduce a small amount of backup capacity, slightly easing storage requirements. OTEC is not part of the base cases but is introduced in the dedicated supply-side scenarios. At moderate cost levels it plays a limited role, complementing other resources, while at the lowest cost level it significantly reduces overall system capacity by substituting a large share of solar and storage.

11.2 General Conclusion

The evaluation of different scenarios against the criteria of reliability, affordability, energy security, and environmental sustainability reveals clear trade-offs between interventions. High solar–storage systems offer reliable supply but are costly and material-intensive. DSM lowers system size and costs but depends on consistent participation. OTEC stands out for its ability to provide firm, local baseload generation, delivering strong gains in reliability and energy security. Its role depends on cost assumptions: while not selected at current high costs, moderate cost reductions already lead to meaningful capacity additions, and at low costs, OTEC significantly reduces the required solar and storage capacities. Biodiesel offers short-term security but remains import-dependent. Environmentally, OTEC scenarios have the lowest land use and emissions due to their offshore nature, while baseline solar–wind systems require more land but remain within suitable eastern areas.

These findings confirm that Bonaire can achieve a fully renewable electricity system by 2030 through a balanced combination of renewable generation, demand-side measures, and targeted flexibility options. Wind and solar form the backbone, while CSP and DSM improve evening reliability and system affordability. In the longer term, OTEC has the potential to become the structural anchor of Bonaire's energy system, providing stable, dispatchable capacity that enhances resilience and reduces dependence on weather conditions and imports. While a solar–wind–storage pathway is technically feasible, a diversified strategy that integrates demand flexibility, transitional backup, and emerging technologies such as OTEC offers a more reliable, affordable, and sustainable long-term energy future. Strategically investing in OTEC development and demonstration after 2030 could secure a resilient and cost-effective foundation for Bonaire's energy transition in the decades ahead.

11.3 Recommendations

A first priority for WEB Bonaire is to strengthen the data foundation for system planning. The current inventory of electricity customers is too limited, making it difficult to design and target demand-side management (DSM) programs effectively. A more detailed registry that links each connection to customer type, location, and size should be developed, allowing the utility to distinguish between households, commercial users, hotels, and industrial consumers. This can be supported by collecting data at the transformer and station level within the existing GIDS system to identify local hotspots of demand and flexibility potential. A similar improvement is needed on the generation side. Current billing records only measure net electricity purchases from the grid, underestimating the actual amount of rooftop PV generation and self-consumption. A systematic inventory of customer-side PV, ideally enabled through smart meters and mandatory production reporting, would provide a more accurate picture of the self-supply already in place. Future surveys should also include simple questions on appliance ownership and typical use patterns for air conditioning, water heating, laundry, dishwashing, pool pumps, and EV charging, translating consumer willingness into concrete DSM schedules. Taken together, these steps would create an integrated dataset that combines smart metering, geographic information, and systematic tracking of PV and storage. Such a dataset would provide a much stronger foundation for precise DSM program design, targeted tariff structures, and robust capacity expansion planning.

Turning to DSM and flexibility implementation, the initial focus should be on households, which together with commercial users account for almost 80 percent of total electricity consumption. Pilot programs for time-of-use tariffs should be introduced to move beyond stated willingness and gather evidence on actual demand elasticity under different price signals. Once more detailed data becomes available, DSM efforts should be expanded to include large customers such as hotel, which represent substantial loads and additional opportunities for flexibility.

In parallel, Bonaire must also make careful generation and technology choices. Biodiesel gensets should be retained as a transitional backup resource throughout the 2020s to safeguard reliability, but their use should gradually decline as renewable alternatives mature. Concentrated solar power (CSP) with integrated storage should be prioritized in the medium term, as it directly addresses the structural challenge of evening demand without creating excessive dependence on batteries. At the same time, Ocean Thermal Energy Conversion (OTEC) remains a promising long-term baseload option. Active monitoring, international partnerships, and pilot projects could position Bonaire as an early mover in this innovative marine renewable technology.

Finally, for long-term system design, the energy system model developed in this research should be integrated into WEB's planning tools as a decision-support system. This would enable scenario analysis and investment planning that explicitly weighs the trade-offs between DSM, generation expansion, and storage. The most promising pathway is a phased transition strategy: DSM as the immediate priority, biodiesel as a transitional hedge for reliability, CSP as the medium-term structural solution for evening coverage, and OTEC as the long-term baseload option. By aligning demand flexibility, renewable deployment, and system planning into a coherent sequence, Bonaire can move toward a stable, affordable, and sustainable energy future.

11.4 Outlook

Bonaire’s energy transition provides valuable lessons for other small island contexts. Achieving a fully renewable electricity system requires more than expanding generation capacity. It depends on the coordinated use of technological, behavioral, and institutional strategies. The island’s strong renewable resources, compact grid, and demonstrated consumer willingness offer a solid foundation for this transition. By combining demand-side measures, transitional reliability options, and emerging marine renewables in a phased manner, Bonaire can build a stable, affordable, and sustainable energy system by 2030. This approach can serve as a model for other Small Island Developing States seeking to align decarbonization with reliability, affordability, and energy security.

The results confirm that reliability and affordability depend on demand flexibility, transitional backup strategies, and the careful integration of new technologies. A stronger data foundation, especially on customer profiles, self-production, and behavioural flexibility, is essential to support this process. By linking technical modelling, stakeholder perspectives, and social insights, this thesis provides practical guidance for Bonaire’s energy future and contributes to the broader academic understanding of small island energy transitions.

AI Statement

While preparing this work, I used ChatGPT to assist with identifying keywords for my literature review and Grammarly to check my spelling and grammar. Additionally, ChatGPT helped me refine my wording in cases where I struggled to articulate my thoughts clearly. After using this tool/service, I reviewed and edited the content as needed and I take full responsibility for the content of my research proposal.

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Appendices

A. Number of Electricity Consumers in Bonaire by Category (2014–2024)

The total number of electricity consumers in Bonaire has grown steadily over the past decade, increasing from 9,373 in 2014 to 13,403 in 2024. This corresponds to an average annual growth rate of around 3–4%. The expansion is mainly driven by the increase in small-scale consumers, which rose from 7,797 to 10,239 over the period. Prepaid electricity users have also grown significantly, more than doubling from 1,461 to 2,991, indicating an increasing adoption of prepaid services. Large-scale consumers show moderate but consistent growth, reflecting the gradual expansion of commercial and industrial activity on the island. This steady rise in total connections underlines the need for forward-looking energy planning to meet growing demand.

Growth in Number of Electricity Consumers in Bonaire by Consumer Category (2014–2024)

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Large-scale consumers	115	116	128	137	144	148	153	164	170	174	173
Small-scale consumers	7797	7962	8048	8190	8266	8574	8943	9336	9626	9888	10239
prepaid electricity service	1461	1660	1868	2068	2267	2,433	2557	2686	2803	2935	2991
Total	**9373**	**9738**	**10044**	**10395**	**10677**	**11155**	**11653**	**12186**	**12599**	**12997**	**13403**
Growth		4%	3%	3%	3%	4%	4%	4%	3%	3%	3%

B. Literature Review Search Process

B1. Keywords Used in Literature Search Strings

Table B1 summarizes the main keywords and search strings used to identify relevant literature. The keywords were grouped into five main categories: renewable energy sources, geographical scope, type of electrical system, energy system criteria, and flexibility options. This systematic combination ensured coverage of both technology-specific studies (e.g., wind, solar, OTEC) and broader system-level discussions (e.g., reliability, flexibility, affordability) relevant to island contexts.

Renewable energy	Geographical scope	Type of electrical System	Criteria of energy system	Flexibility options
Renewable Energy	Island	Island Energy Systems	Grid Stability	Flexibility
Wind Energy	Bonaire	Microgrid	Reliability	Balancing
Solar Energy	Curacao	Islanded mode	Affordability	Demand Response, Demand, Demand-side management,
Sustainable Energy	Aruba	Decentralized Grids	Cost-effective	Battery Storage, Energy Storage
Wave Energy	Dutch Caribbean	Island Grids	Resilience	Electric Vehicles, EV
Ocean Energy	Netherlands Caribbean	Off-grid	Security	Backup Systems, Flexible and dispatchable generation, Reserve Capacity
Green Energy	Caribbean	Independence	Balancing	
Tidal Energy	Netherland Antilles	Grid	Self-sufficient	
PV, Photovoltaic		Power system	Optimal	
Carbon-Free Energy		Energy system	Optimization	
Marine Energy				
Blue Energy				
Hydrokinetic Energy				
Zero-carbon energy				
Biomass				
Biodiesel				

B2. Search Strategy and Selection Process

The literature search was conducted using **Scopus** on **2 December 2024**, following a structured process of identification, screening, and eligibility, inspired by systematic review approaches.

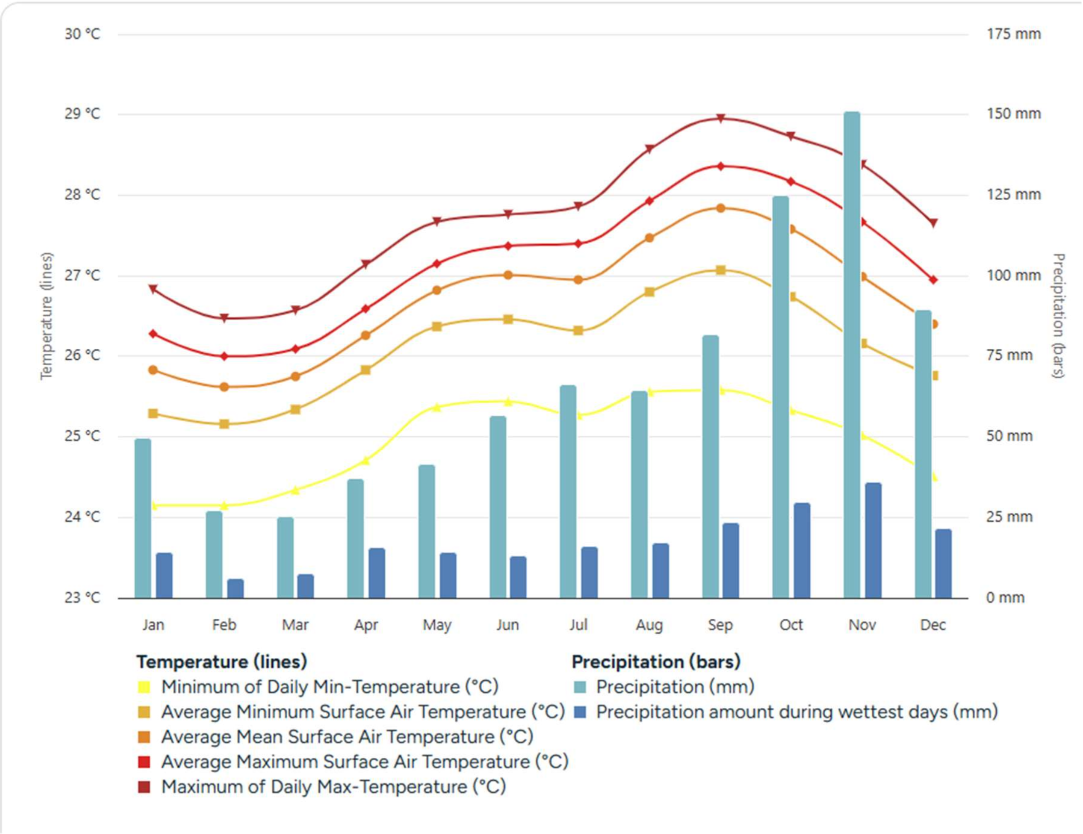
Scopus **2-12-2024**	**Search string**	**No. of documents**
Identification The first search string targeted studies addressing renewable energy integration in island systems, ensuring they included discussions of energy system criteria or flexibility options.	TITLE-ABS-KEY (("Renewable Energy" OR "Wind" OR "Solar" OR "Sustainable" OR "Wave" OR "Ocean" OR "Green Energy" OR "Tidal" OR "PV" OR "Photovoltaic" OR "Carbon-Free " OR "Marine" OR "Blue Energy" OR "Hydrokinetic Energy" OR "Zero-carbon energy" OR "Biomass" OR "Biodiesel") AND ("Island" OR "Bonaire" OR "Curacao" OR "Aruba" OR "Dutch Caribbean" OR "Netherlands Caribbean" OR "Caribbean" OR "Netherlands Antilles") AND ("Island Energy Systems" OR "Microgrid" OR "Island*" OR "Decentralized Grids" OR "Island Grids" OR "Off-grid" OR "Independence" OR "Grid" OR "Power system" OR "Energy system") AND ("Stability" OR "Reliability" OR "Affordability" OR "Cost-effective" OR "Resilien*" OR "Security" OR "Balancing" OR "Self-sufficient" OR "Optimal" OR "Optimization") OR ("Flexibility" OR "Demand and Response" OR " Storage" OR "Electric Vehicles" OR "EV" OR "Demand" OR "Backup Systems" OR "Flexible" OR "Dispatchable generation" OR "Reserve Capacity" OR "Battery Storage" OR "Balancing" OR "Demand-side"))	4,163
Screening A subsequent search focused specifically on articles that emphasized energy system criteria relevant to the sustainability, reliability, and affordability of energy systems.	Renewable energy AND Geographical scope AND type of electrical system AND Criteria OR flexibility options	2,862
Another search string aimed to identify studies exploring both energy system criteria and flexibility options, providing a more comprehensive view of solutions for grid stability and demand-supply balance.	Renewable energy AND Geographical scope AND type of electrical system AND Criteria AND flexibility options	1589
To narrow the scope and capture studies relevant to the Caribbean context, the term "island" was eliminated from the search string, focusing instead on literature addressing renewable energy systems in the Dutch Caribbean or similar regions.	Eliminating keyword island for geographical scope from search string	30
Eligibility Full-text review to assess if the articles are specifically relevant to Bonaire's renewable energy system,	Excluded studies focused on temporary energy supply solutions related to hurricanes, those not centered on island-based systems, topics emphasizing climate resilience without direct relevance to energy systems, geopolitical or historical energy dependency, education programs, energy systems for ships.	
Included		13

C. Meteorological Conditions on Bonaire

Understanding Bonaire's meteorological conditions is essential for accurately representing both electricity demand patterns and the potential performance of renewable energy technologies. Temperature strongly influences cooling demand, while wind speeds and solar irradiance determine the availability of wind and solar power resources throughout the year. The following subsections present the main climatic patterns that shape the island's energy system dynamics.

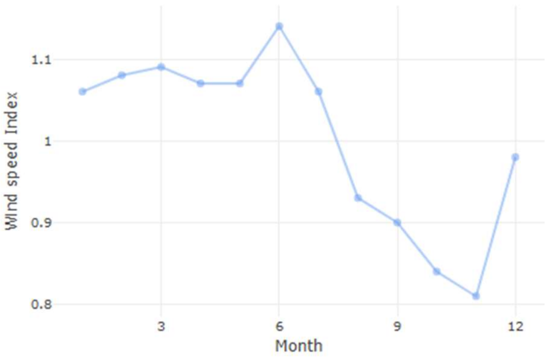
C1. Monthly Temperature Patterns in Bonaire

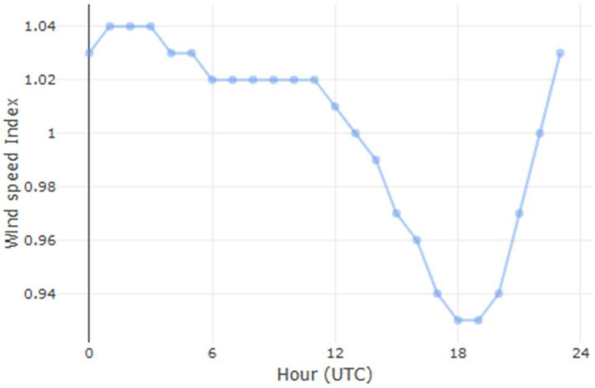
Figure C1 shows the monthly temperature patterns on Bonaire. Temperatures remain warm throughout the year, with September standing out as the hottest month. During this period, average daily maximum temperatures reach around 29 °C, while minimum temperatures also remain elevated. These consistently high temperatures drive increased cooling demand, making September the system's annual peak demand month. *Source: Bonaire, Sint Eustatius and Saba (BES) – Climatology (ERA5), Climate Change Knowledge Portal (n.d.).*



C2. Seasonal and Diurnal Wind Speed Patterns in Bonaire

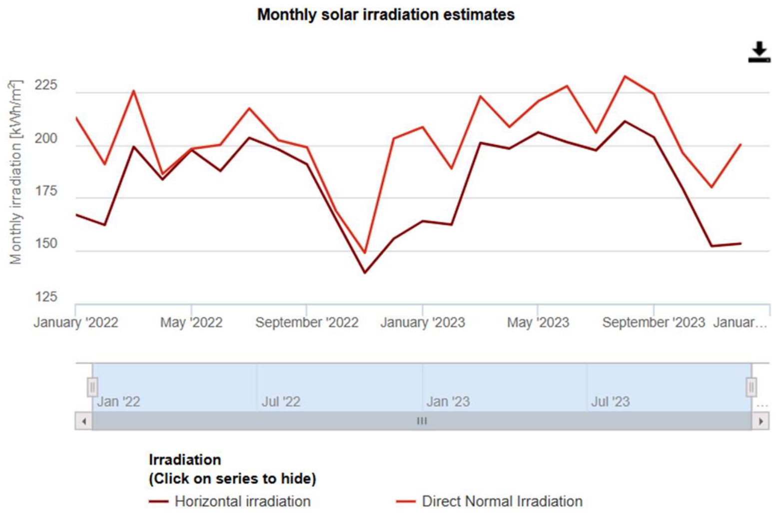
Figures C2 presents the seasonal and diurnal variation of wind speeds. Seasonally, wind speeds are higher in mid-year and lower toward the end of the year. Diurnally, winds are strong during nighttime and early morning hours. These patterns are relevant for estimating wind generation potential and understanding its complementarity with solar resources. *Source: Global Wind Atlas (n.d.).*

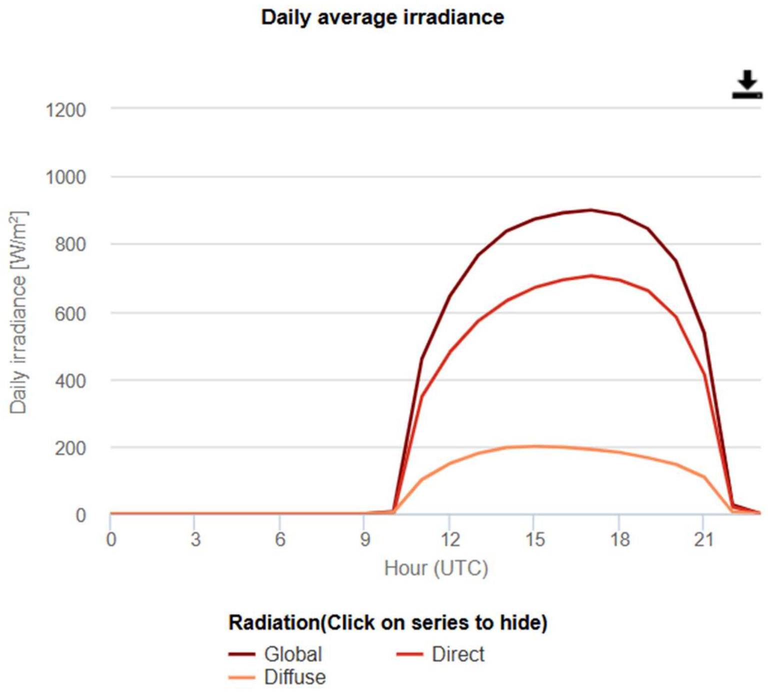




C3. Monthly and Hourly Solar Irradiation Patterns in Bonaire

Figure C3 displays both monthly and hourly solar irradiation estimates for Bonaire (2022–2023). Monthly values are relatively high and stable year-round, with a noticeable seasonal dip in November. Hourly averages show clear daily cycles, with global, direct, and diffuse components peaking around mid-day. These patterns highlight the consistency and predictability of solar resources on the island. *Source: JRC Photovoltaic Geographical Information System (PVGIS), European Commission (2016).*





D: **Example of DSM Information Approach (August 2023)**

WEB and CGB issued a public appeal during peak demand conditions in August 2023, asking consumers to reduce and shift electricity use through simple actions. This represents an information-based DSM strategy, but its actual effectiveness in reducing load was not tested or measured.

WEB and CGB are working hard to guarantee the continuity of the energy supply for the island of Bonaire and meet unprecedented demand

Kralendijk, August 28th, 2023 – Excessive heat of the last few days is pushing demand to unprecedented levels and putting the energy supply under pressure.

As we enter the hottest season of the year, hurricane activity is increasing and the wake of several recent hurricanes leads paradoxically to very low wind speeds on the island, reducing the amount of energy that can be produced by the wind turbines at Morotin. Coupled with peak demand for air conditioning, the energy supply situation on Bonaire has become uniquely challenging.

Water -en Energie Bedrijf Bonaire (WEB) and ContourGlobal Bonaire (CGB) are working hard to guarantee the continuity of the energy supply for the island during this period of unprecedented demand. While the organizations do not expect supply to be curtailed, in the worst-case scenario, some areas could be temporarily disconnected if the demand exceeds the generation capacity. The disconnection will be according to a predefined schedule and sequence.

We ask that everyone consider their energy usage and where possible reduce energy consumption as much as possible during this time;

- *Turning off lights and unplug electronics when not in use*
- *Check if your light bulbs are energy efficient, if not change them to more energy efficient bulbs/LED*
- *Adjust thermostat settings to reduce cooling cost by ensuring that the inside temperature (23°C) is not more than 10-degree difference to the outside temperature (33°C). Setting your air conditioner at a lower temperature will also result in a higher electricity bill.*

By doing so you can help maintain the energy supply to all customers and lower your energy bill at the end of the month.

E. Survey Results

To better understand current energy use, self-generation, and flexibility potential on Bonaire, Water en Energiebedrijf Bonaire (WEB) conducted surveys among households and large consumers. These surveys provide valuable insights into the adoption of renewable technologies, energy-saving practices, and willingness to participate in demand-side management measures, which are essential for planning the island's energy transition. (WEB, May 2025)

E1. Household Survey

The **household customer satisfaction survey**, conducted by WEB in **May 2025**, included questions on demographic characteristics, ownership of solar panels, batteries, and electric vehicles, awareness of feed-in tariffs, adoption of energy-saving measures, and willingness to adapt consumption to time-of-use pricing or peak conditions. The responses provide a clear picture of consumer behavior and attitudes toward flexibility on the island.

Category	***Results***
Respondents	791 respondents completed the satisfaction survey for private households
Gender	More women than men filled in the questionnaire (women: 53%, men: 44%, unknown: 3%)
Residence	Respondents live spread across Bonaire. Distribution over neighborhoods is similar for 2022, 2023, and 2025 with small differences (Antriol, Nikiboko, Noord Salina, Playa, Rincon, Tera Cora, Unknown)

OWN ENERGY SUPPLY	**RESULTS**
SOLAR PANELS	15% of respondents have solar panels (stable: 17% in 2022, 15% in 2023, 15% in 2025)
BATTERY STORAGE	5% of respondents who generate their own energy have a battery
ELECTRIC CAR	2% of respondents own an electric car
AWARENESS OF FEED-IN TARIFF	67% of respondents with own energy supply know about the possibility of receiving compensation for fed-back energy

ENERGY-SAVING MEASURES	**RESULTS**
APPLY ONE OR MORE MEASURES	**52%** of respondents take energy-saving measures (down from 65% in 2022 and 67% in 2023)
TYPES OF MEASURES	• Presence switch(9%) • **LED lighting (~45%)** (most common) • **Inverter air conditioning (~42%) • Roof/wall/window insulation (~15%)** • Other smaller measures

TIME-OF-USE (TOU) PRINCIPLE	RESULTS
WILLINGNESS TO ADAPT ENERGY USE	68% of respondents are willing to adjust energy use according to peak-hour approach
RESPONSE DISTRIBUTION	• 42%: Yes, I shift usage to off-peak hours or reduce during peak hours • 24%: Only if explicitly requested (e.g., during high demand caused by extreme heat) • 29%: No, I would not adapt usage during peak hours • 2%: Unknown

E2. Large Customer Survey

The **large customer survey**, also carried out by WEB, targeted commercial, industrial, and institutional users to assess their existing energy infrastructure, such as backup generation and self-generation, as well as their energy-saving practices and future investment intentions. These responses highlight the role of large users as both significant consumers and potential contributors to flexibility and local renewable generation.

Category	**Results**
Respondents in database	136 large users with a phone number in WEB's records
Survey completed	38 large users filled in the questionnaire
Response rate	28%
Sectors of Respondents	
Agriculture & fisheries	1
Industry	1
Production & distribution of electricity and chilled air	2
Construction	3
Wholesale & retail	2
Transport & storage	2
Hospitality (Horeca)	5
Real estate rental & trade	4
Financial institutions	2
Education	6
Health & welfare	3
Other services	9
Unknown	2

LARGE USERS: OWN ENERGY SUPPLY	**PERCENTAGE**
HAS A POWER BACK-UP SUPPLY IN THE FORM OF A GENERATOR	**40%**
GENERATES ITS OWN ENERGY THROUGH SOLAR PANELS OR WIND TURBINES	**34%**
PLANS TO INSTALL SOLAR PANELS WITHIN THE NEXT 5 YEARS	**37%**

ENERGY-SAVING MEASURES BY LARGE USERS	**RESULTS**
APPLY ONE OR MORE MEASURES	**89%** of respondents take energy-saving measures (same as in 2023, but more methods used)
BREAKDOWN OF MEASURES	**• LED lighting – 22% • Energy-efficient cooling – 27% • Roof/wall/window insulation – 6% • Presence switch – 17% •** Other smaller measures

F. Large Consumers and Demand-Side Flexibility Potential

This section analyses large electricity consumers on Bonaire, focusing on their consumption patterns and potential for demand-side flexibility. While these sectors play a significant role in the island's overall energy demand, they were excluded from quantitative modelling due to incomplete data and the wide diversity of activities across commercial, industrial, and hospitality users. This heterogeneity makes it challenging to systematically assess flexibility potentials, so the analysis presented here is qualitative and exploratory in nature.

Bonaire's load shows two distinct peaks with different drivers: the afternoon peak (14:30–16:30) is largely associated with commercial, industrial, and public-sector activity, while the evening peak (19:30–21:30) is predominantly residential as people return home. The next section examines the large consumers and their DSM/DR flexibility potential.

Commercial customers

In 2024, 145 commercial sites on Bonaire consumed between 5,000 and 500,000 kWh. For analysis, sites were grouped by the nature of operations—company type, sector, and function, rather than detailed industrial processes (Web internal data).

The upper band (50,000–500,000 kWh) contains roughly ten users with moderate-to-high operational demand. It is led by the hospital, the only commercial site above 250,000 kWh, driven by 24/7 medical services, climate control, and specialized equipment. Other prominent users in this band include supermarkets, hotels/resorts, the airport, salt production, and telecommunication/utility control facilities. Public utilities such as sewage treatment and water purification plants contribute steady baseloads essential to public health.

The medium band (10,000–50,000 kWh) includes many public-sector facilities—police stations, fire stations, administrative offices , primary and secondary schools and construction/housing-development firms. Loads in this tier are mainly lighting, HVAC, and ICT/office equipment during extended daytime hours. Larger campuses or near-continuous services can fall into the upper band, while small satellite offices may sit below 10,000 kWh.

The lower band (5,000–10,000 kWh) is diverse: offices, retail and service shops, banks, gyms, childcare centers, churches, museums, small apartment complexes, snack bars, and small restaurants. Individually modest, these sites are significant in aggregating within the commercial landscape.

Industrial

In addition to commercial users, a small group of industrial customers was identified by WEB's customer service department. Boundaries between sectors are fluid: some entities are clearly industrial, while many operate in a hybrid space that overlaps with commercial activity. Classification is further complicated by data limitations, since the billing-oriented records were not designed for demand studies, so category labels and quality controls are imperfect.

industrial includes essential utility infrastructure such as water treatment and distribution, fuel storage and supply, and vacuum and pumping systems that require continuous, stable electricity and therefore contribute to the island's baseline load. It also covers real-estate developers, property managers, and construction-related organizations, and in some cases public institutions with substantial operational infrastructure. Large hospitality sites such as resorts and hotels may appear under industrial influence because of the scale and intensity of laundry, kitchens, and logistics. Retail and food-service enterprises, including supermarkets, cafés, and wholesalers, can be classified as industrial when they operate cold storage, commercial kitchens, or warehousing. Other contributors include automotive garages, transport and logistics firms, and cleaning or facility service providers.

Within this landscape, the largest customers in this category form a mid-scale cohort of twelve companies with annual electricity use between 10,000 and 80,000 kWh, comprising a wholesale import and logistics firm, several resort and hospitality establishments, a supermarket with cold storage, food-service businesses, a real-estate development firm, and public facilities including a government building and a vacuum station tied to utility infrastructure.

Hospitality

Tourism is the backbone of Bonaire's economy, accounting for roughly 50% of gross domestic product (GDP) and employment. An estimated 7,200 jobs are tourism-dependent, and the Visitor Entry Tax alone contributes about 44% of local tax revenues (Mak et al., 2025). This estimate includes both direct and indirect tourism expenditure. The economic importance of tourism is widely recognized by Bonaire's residents, who generally support continued growth in the sector as a driver of job creation and business development. Forecasts indicate steady expansion, with tourist arrivals projected to reach approximately 201,969 by 2028, representing an average annual growth rate of 3.6% over 2024–2028 (BMI Fitch Solutions, 2024) (figure F1) .

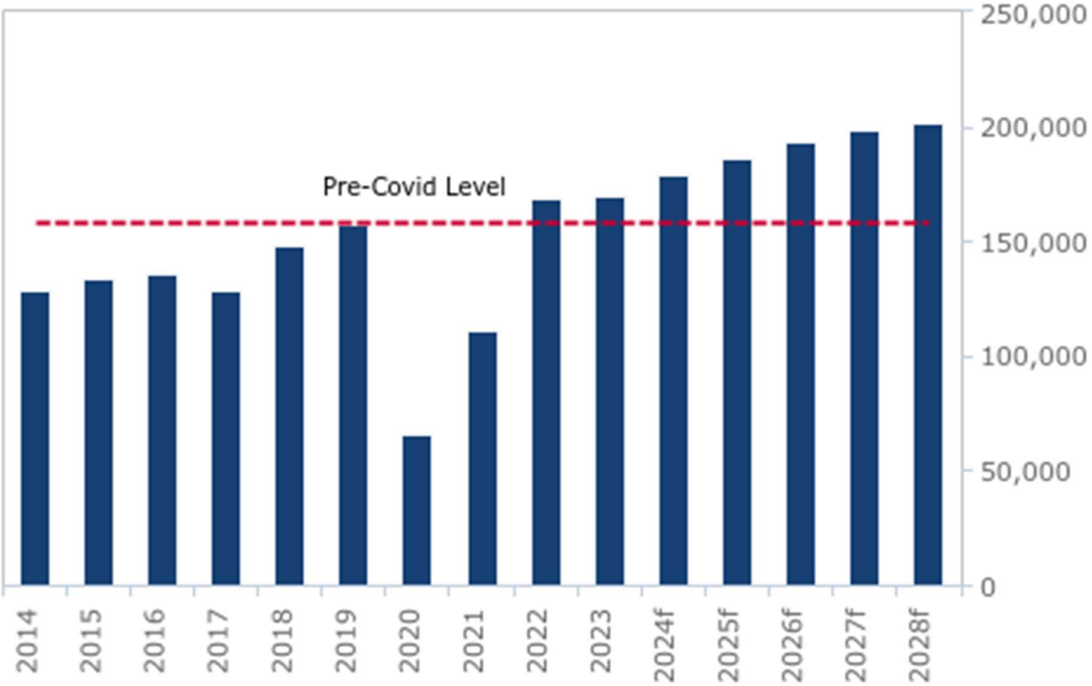


Figure F1: Forecast of tourism growth in Bonaire, showing a sharp decline in 2020 due to the COVID-19 pandemic, followed by recovery to pre-COVID levels in 2022 and steady growth projected through 2028 (BMI Fitch Solutions, 2024).

The central role of tourism also makes the hospitality industry one of the largest consumers of energy on the island. Hotels, resorts, and apartment complexes together account for about 7.5% of Bonaire's total energy consumption directly, while also present in the commercial and industrial sectors. This high level of demand and forecasted growth highlights its potential role in providing flexibility within Bonaire's future renewable energy system.

As shown in Figure F2, data from the Caribbean Hotel Energy Efficiency Action Program highlights the distribution of electricity consumption by end use across hotels of different sizes (Tetra Tech, 2012). Air conditioning is by far the largest contributor, accounting for between 43% and 53% of total electricity demand depending on hotel size. The second-largest share is typically lighting, which ranges from 9% to 13%, followed by kitchen and refrigeration equipment (8–12%), and guestroom equipment (6–9%). Other significant but smaller contributors include pool pumps (4–10%), hot water and laundry (4–6%), and general equipment (4–7%). The results indicate that regardless of hotel size, energy use in the hospitality sector is highly concentrated in cooling.

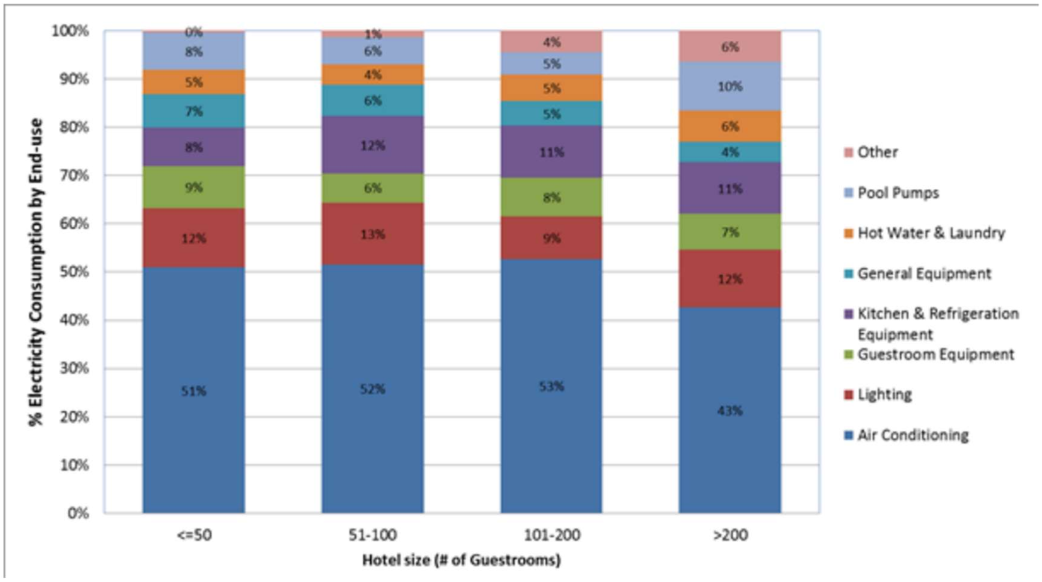


Figure F2: Electricity consumption by end use in Caribbean hotels of different sizes, with air conditioning as the dominant load (43–53%), followed by lighting, kitchen and refrigeration, and guestroom equipment. Larger hotels (>200 rooms) show relatively lower shares of air conditioning but higher contributions from pool pumps and general equipment (Tetra Tech, 2012).

Large consumers end use and potential for demand flexibility

Previously in this chapter, large customers were introduced: commercial, industrial, and hospitality. Here they are treated using the same end-use framework as the residential sector, with DSM and DR potential identified for each end use. Table F summarizes typical electricity end uses in these three customer groups and how demand-side measures can reduce or shift demand: DSM refers to permanent efficiency and control actions that lower the baseline, while DR refers to operational adjustments that move flexible loads out of peaks. A common scheduling convention applies across sectors: avoid peaks at 14:30–16:30 and 19:30–21:30; use 22:00–14:00 as the primary off-peak window; and treat 17:00–19:00 as a limited pre-cooling period rather than a slot for other heavy loads. The guiding rule is shift or self-supply: loads may run during peaks only when served by on-site PV, batteries, or V2G-enabled EVs so that net grid draw remains zero.

Table F: Assessment of demand-side flexibility opportunities for large customers in Bonaire. The main DSM/DR potential lies in HVAC, cooking, laundry, and pumping systems, while lighting, ICT, water heating, and tools offer more modest contributions. Refrigeration, though a major load in retail, food, and hospitality sectors, provides only limited flexibility due to its need for continuous operation.

End-use	**Sector groups where most relevant**	**Demand Flexibility potential (DSM/DR)**
HVAC	Offices & Services; Retail & Food; Hospitality; Healthcare; Education; Entertainment; Transport & Logistics	DSM+DR: Pre-condition in 22:00–14:00 to avoid 14:30–16:30; pre-cool 17:00–19:00, then set-back 19:30–21:30; resume normal after 22:00. Tune setpoints and use fans to coast through the peak.
Refrigeration	Retail & Food; Logistics & Wholesale (cold rooms); Hospitality; Industrial & Light Processing; Transport & Logistics	DSM limited: Efficient cases/condensing units, tight seals; optimize setpoints/defrost. DR (limited); minimize door openings near peaks.
Lighting (indoor/outdoor/security)	All commercial groups	DSM: LEDs, occupancy/daylight controls, task lighting. DR (limited): Dim/switch non-critical lighting during peaks; schedule signage/cleaning in 22:00–14:00.
ICT, servers & telecom cooling	Offices & Services; Utilities & Telecom; Education; Airport	DSM (limited): Efficient servers/PSUs, right-size cooling.
Cooking & commercial kitchens	Retail & Food; Hospitality; Healthcare; Education	DSM limited +DR limited: Shift prep/batch cooking to 22:00–14:00; avoid heavy cooking in peak windows where feasible.
Laundry (washers, dryers, ironers)	Hospitality; Healthcare; Cleaning & Maintenance Services; Industrial laundry; Education (boarding)	DR+DSM: Run cycles in 22:00–14:00; avoid 14:30–16:30 and 19:30–21:30. Upgrade to high-efficiency machines
Pumps, blowers & motors (incl. pool pumps)	Utilities (water/fuel/pumping); Hospitality (pools); Industrial & Light Processing (incl. salt production)	DSM: Motor/pump upgrades. DR: Timers/scheduling in 22:00–14:00; avoid stacking large drives at peaks while maintaining minimum service.
Water heating (electric)	Hospitality; Food Services; Healthcare; Offices & Services	DR limited + DSM: Storage heaters: heat in 22:00–14:00; lower setpoints; insulate tanks/pipes. Tankless: limited shift.
Tools & compressors	Construction & Development; Automotive & Mechanical Services; Logistics yards	Limited DSM+ DR

H Storage Technology Cost Assumptions

The table below presents the technical and cost assumptions for storage technologies applied in the model. Technologies differ in round-trip efficiency, calendar lifetime, and storage duration, reflecting their operational characteristics. Cost assumptions are shown for different project sizes (1 MW, 10 MW, 100 MW, and 1000 MW) to capture economies of scale, as larger systems benefit from significantly lower unit costs.Investment costs (CAPEX) are annualized using a WACC of 8.7% and the technology-specific lifetime, then divided by 12 to obtain monthlyized costs, consistent with the one-month simulation period. These monthlyized values represent the cost of owning and operating 1 MW of storage capacity per month, including fixed O&M. The assumptions form the basis for all storage investments in the scenario analysis.(Pacific Northwest National Laboratory et al., 2022)

Technology	Round-trip Efficiency (%)	Calendar Life (years)	Duration (hours)	1 MW – Capital Cost ($/MWh)	1 MW – Fixed O&M Cost ($/MWh·year)	1 MW – CAPEX + Fixed O&M ($/MW·month)	10 MW – Capital Cost ($/MWh)	10 MW – Fixed O&M Cost ($/MWh·year)	10 MW – CAPEX + Fixed O&M ($/MW·month)
Li-ion BESS (existing)	85	**-**	0.64 (14 MW / 9 MWh)						
Li-Ion NMC	**85**	**15**	2	440,950	2,930	9,284	393,360	2,600	8,281
			4	381,350	4,750	16,031	349,950	4,340	14,709
			6	368,000	6,550	23,178	339,940	6,050	21,494
			8	355,000	8,340	29,805	330,330	7,760	27,734
			10	342,300	10,140	35,931	320,720	9,470	33,663
Li-Ion LFP	**85**	**15**	2	398,980	2,690	8,403	353,580	2,370	7,413
			4	340,460	4,280	14,316	311,110	3,890	13,079
			6	327,780	5,850	20,647	301,680	5,360	19,000
			8	315,100	7,420	26,373	292,230	6,720	24,523
			10	302,420	8,990	31,830	282,830	8,280	29,680
Lead Acid	78	10	2	533,640	3,960	14,050	481,560	3,470	12,668
			4	458,840	6,090	24,086	423,350	5,500	22,221
			6	442,560	8,180	34,796	410,470	7,490	32,231
			8	426,290	10,280	44,611	397,510	9,480	41,635
			10	410,010	12,370	53,732	384,630	11,470	50,433
Vanadium Redox Flow	65	12	2	695,900	4,990	16,306	634,530	4,490	14,796
			4	486,850	6,600	22,783	449,550	6,030	21,007
			6	445,040	8,150	31,163	412,550	7,560	28,890
			8	403,230	9,680	37,569	375,570	9,100	35,060
			10	361,420	11,230	42,115	338,570	10,630	39,539
Zinc	70	15	2	520,890	9,030	11,431	484,650	8,960	10,682
			4	416,580	18,330	18,607	384,990	18,790	17,350
			6	408,500	15,730	26,434	379,980	15,987	24,701
			8	400,420	13,130	33,929	374,970	13,183	31,846
			10	392,340	10,530	41,092	369,960	10,380	38,786
	Round-trip Efficiency (%)	**Calendar Life (years)**	**Duration (hours)**	**100 MW – Capital Cost ($/MWh)**	**100 MW – Fixed O&M ($/MW·yr)**	**100 MW – CAPEX + Fixed O&M ($/MW·month)**	**1 000 MW – Capital Cost ($/MWh)**	**1 000 MW – Fixed O&M ($/MW·yr)**	**1 000 MW – CAPEX + Fixed O&M ($/MW·month)**
Gravitation	83	45	4	403,410	23,600	15,396	237,790	16,040	9,317
			10	275,990	30,930	25,608	166,370	23,370	15,872
Thermal	52	35	4	560,490	9,610	19,535	367,450	6,250	12,844
			10	271,680	29,110	25,094	200,220	21,740	18,471
Hydrogen	35	30	**10**	101,460	14,300	9,684	101,000	7,980	9,077

I **Monthlyized and Lifetime System Costs under 6% Demand Growth (G6)**

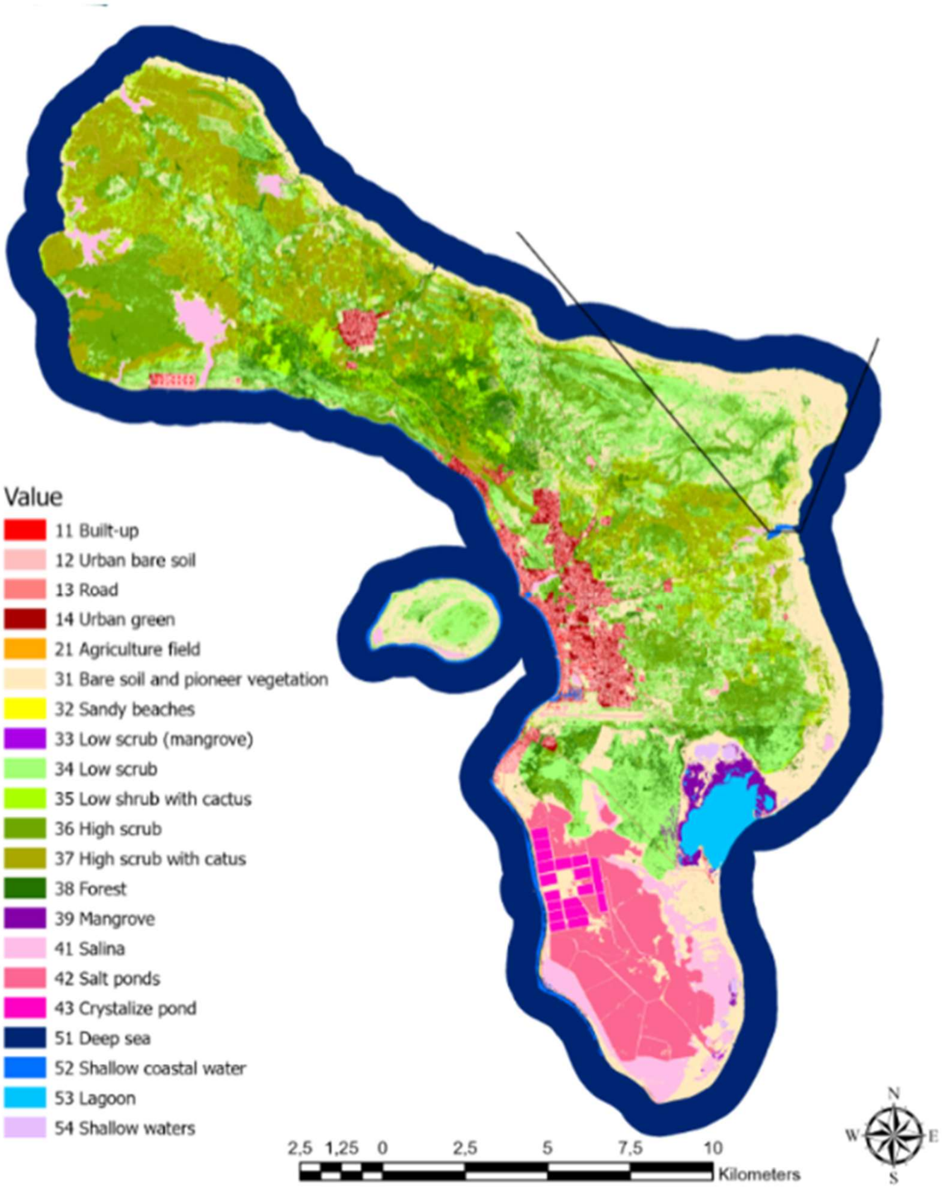
This table presents monthlyized system costs, levelized costs per kilowatt-hour, and lifetime Net Present Values (NPV) over 30 years for all intervention scenarios under the high demand growth (G6) pathway. Costs are based on the September stress month and include both CAPEX and fixed O&M, annualized using a WACC of 8.7 %.

Scenario	***Monthlyized Cost***	***Cost $/kWh)***	***Annual Cost (M $)***	***30-Year NPV (M $)***
Baseline	3.24 M $	0.1609 $/kWh	38.9 M $	416 M $
DSM – Low	2.99 M $	0.1568 $/kWh	35.9 M $	384 M $
DSM – Medium	2.83 M $	0.1538 $/kWh	33.9 M $	363 M $
DSM – High	2.58 M $	0.1490 $/kWh	31.0 M $	332 M $
Decentralized Storage	3.23 M $	0.1605 $/kWh	38.8 M $	414 M $
OTEC (11.02 M $/MW)	2.67 M $	0.1325 $/kWh	32.0 M $	341 M $
OTEC (15 M $/MW)	3.10 M $	0.1536 $/kWh	37.2 M $	398 M $
OTEC (25.9 M $/MW)	3.24 M $	0.1609 $/kWh	38.9 M $	416 M $
Biodiesel Backup	3.24 M $	0.1609 $/kWh	38.9 M $	416 M $

J Spatial Maps of Bonaire for Renewable Energy Site Selection

Together, these maps support spatial assessment for identifying low-conflict zones for renewable energy development on Bonaire. By overlapping open landscape areas with land cover data, planners can prioritize sites that minimize impacts on natural ecosystems, protected areas, and urban infrastructure, while taking advantage of existing degraded or open land.

This map displays detailed land use and vegetation classes across Bonaire (Smith et al., 2012). The classification includes built-up areas, roads, agricultural fields, various scrub and forest types, mangroves, salinas, and coastal/marine zones. Of particular interest are class 31 (Bare soil and pioneer vegetation) and class 34 (Low scrub), which align with the open landscape zones identified in Figure X.1. These areas are considered preferred locations for renewable energy infrastructure, as they are less ecologically sensitive compared to forests, mangroves, salinas, or urban zones. (*Dutch Caribbean Biodiversity Database*, n.d.)



This map illustrates the spatial distribution of nature areas, national parks, Ramsar sites, caves, and open landscapes across Bonaire. Areas highlighted in green represent designated nature zones, while striped, green indicates national park boundaries. Orange areas correspond to open landscapes, primarily consisting of low scrub and bare soil/pioneer vegetation. These open landscape zones are identified as potentially suitable areas for renewable energy development, whereas nature reserves, national parks, Ramsar sites, and cave zones should be avoided to prevent ecological disturbance.

(Smith et al., 2012)