Exploring the techno-economic feasibility of OTEC in Aruba's renewable energy transition

Combining power system modelling and stakeholder and institutional analysis

MSc. Sustainable Energy Technology

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Delft University of Technology

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This is not the end, this is not even the beginning of the end, but it is perhaps the end of the beginning.

Timo Scheepmaker
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Executive Summary

Ocean Thermal Energy Conversion (OTEC) is a *renewable energy technology* (RET), that harnesses energy from the temperature differences between warm surface and cold deep-sea water. OTEC can generate a continuous stream of renewable electricity, functioning as a baseload energy source. To achieve this the ocean water temperature difference must be at least 20°C, favouring locations close to the equator where surface water temperatures are typically higher. *Small Island Developing States* (SIDS) such as Aruba have been identified as potential markets for OTEC, as many of them are located within such regions and exhibit favourable conditions for OTEC.

OTEC has the highest ocean energy resource potential of all ocean energy technologies. However, of the 44PWh/year in global resource potential very little is being harnessed. With OTEC currently in a pre-commercial phase it has faced challenges advancing to the commercial phase. A large contributing factor to this is a lack of financing and government support for the technology. The technology has a high capital cost with a relatively modest amount of operational plants built to date, providing a limited track record. Furthermore, on smaller scales the technology is generally not economically viable as it experiences considerable economies of scale, becoming substantially more economic with larger plant capacities. This results in a phenomenon known as the “valley of death” where smaller pre-commercial OTEC plants are not commercially attractive but results from such facilities are needed to convince financiers that the risk of building such plants is manageable.

To overcome this “valley of death” research exploring the technological and economic feasibility of implementing OTEC is vital to bolster confidence among investors and governmental bodies. This thesis project aims to contribute to this by conducting a techno-economic, power system model and stakeholder and institutional analysis exploring OTEC’s implementation in Aruba with the main research question:

Is it technically and economically feasible to implement OTEC in Aruba’s energy system and if so what technical, economic and social factors play a role?

The research is conducted using power system modelling as well as qualitative analysis. A conceptual model of Aruba’s power system based on fully renewable technologies has been developed in a modelling and simulation tool. In this work on and offshore wind, land-based utility scale and floating PV and OTEC are analysed with *Battery Energy Storage System* (BESS) for storage capacity. The model has been formulated as an optimisation of a generation problem to assess cost-optimal solutions for generation investments to meet demand while satisfying all constraints. This is firstly done for a reference scenario in 2030, 2040 and 2050 and subsequently for alternative scenarios in 2050. Based on these optimisation and stakeholder and institutional analysis results, the feasibility of OTEC’s implementation in Aruba is evaluated and recommendations are provided on whether and how OTEC could be implemented.

This research concludes that OTEC could play a considerable role in Aruba, lowering the levelised system costs of a fully renewable energy system in 2050 from 150 USD/MWh to 96 USD/MWh. The resulting system mix based on electricity generated could consist of 70% OTEC, 9% onshore wind and 21% utility scale land based solar PV. The high share of OTEC in the system is contributed to overlapping periods of low solar and wind resources, which lead to high storage costs if no baseload such as OTEC is implemented, also known as ”dunkelflaute”. Moreover, the size of the OTEC plant implemented is found to be critical with plants below 35 MW_{gross} no longer being cost efficient without subsidies. Furthermore, including fossil fuels in the system has a strong effect on the deployment of OTEC as it is no longer cost efficient to deploy OTEC with a renewable share lower than 50%. The implementation of OTEC is therefore heavily dependent on two conditions: 1) the government of Aruba must set a clear target to achieve more than 50% renewable energy for electricity generation by 2050, and 2) OTEC must advance to the commercial stage, with 35+ MW_{gross} plants available, or financial support in the form of subsidies or grants must be provided for smaller plants. Lastly, based on the stakeholder and institutional analysis, a 40-50 MW_{gross} plant is identified as the most feasible and economically viable for Aruba by the early 2050s.

This research has several limitations to be addressed in future research. Firstly, transmission and distribution lines are not included in the model. Secondly, alternative storage technologies such as hydrogen are not included in the model. Thirdly, behind-the-meter technologies such as rooftop solar PV are not included in the analysis. Fourthly, recent demand profiles (post-2017) of Aruba are not openly available. Lastly, the model optimisation and expert consultations do not cover a number of potentially interesting topics such as black/brown-outs, offshore marine traffic and the public reaction towards the implementation of RETs on and around the island.

To enhance this research, three avenues are recommended. Firstly, address the model's current limitations, such as incorporating transmission and distribution networks as well as alternative storage technologies. Secondly, explore the implications of the identified ”dunkelflaute” phenomenon on other SIDS and examine the role OTEC could play in regions lacking viable renewable baseload options. Finally, expand the qualitative analysis by including interviews with potential independent power producers, which would provide a more comprehensive understanding of stakeholder interactions. Moreover, three industry recommendations are formulated. Firstly, consider OTEC's relevance for SIDS that have high RET penetration rates. Secondly, establish strong communication channels with local governments and provide them with relevant expertise. Lastly, compensate OTEC developers based on capacity availability rather than the usual energy generated.

List of Abbreviations

ACF	Aruba Conservation Foundation
BESS	Battery Energy Storage System
Capex	Capital Expenditures
CAGR	Compounded Annual Growth Rate
CC	Closed Cycle
CF	Capacity Factor
CIF	Climate Investment Fund
CWP	Cold Water Pipe
DEZHI	Department of Economic Affairs, Commerce, and Industry
DIP	Department for Infrastructure Management and Planning
DNM	Department of Nature and Environment
DSA	Directie Scheepvaart Aruba
DSW	Deep Sea Water
DOW	Dienst Openbare Werken
DTI	Department for Technical Inspection
EEZ	Exclusive Economic Zone
ESOM	Energy System Optimisation Model
EST	Energy Storage Technologies
GCF	Green Climate Fund
GDP	Gross Domestic Product
GIS	Geographic Information System
HFO	Heavy Fuel Oil
IDB	Inter-American Development Bank
IPP	Independent Power Producer
JETP	Just Energy Transition Partnership
KRISO	Korean Research Institute of Ships and Ocean Engineering
LCOE	Levelised Cost of Electricity
LCoS	Levelised Cost of the System
LNG	Liquefied Natural Gas
NGO	Non-Governmental Organisation
NIMB	Not In My Backyard
OC	Open Cycle
Opex	Operational Expenditure
OTEC	Ocean Thermal Energy Conversion
PoC	Proof of Concept
PWh	Petawatt-hours
PPP	Public-Private Partnership
PSH	Pumped Storage Hydropower
RE	Renewable Energy
RECIP	Reciprocating engine
RES	Renewable Energy Source
RET	Renewable Energy Technology
SD	Sustainable Development
SIDS	Small Island Developing State
SISSTEM	Sustainable Island Solutions through STEM

SoC	State of Charge
SWAC	Sea Water Air Conditioning
TNO	Nederlandse organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek
TW	Tera-watt
VRE	Variable Renewable Energy

Contents

List of Figures

List of Tables

1

Introduction

1.1. Global potential of OTEC technology

In 2023, global electricity consumption was estimated at 27.6 *petawatt-hours* (PWh) [1]. A growing share of this energy demand is being met by renewable energy sources (*RES*), with technologies such as wind power and solar *photovoltaic* (PV) leading the way. These technologies have become central to sustainable energy production globally over the past decade [2]. However, these approaches are not universally applicable and have limitations, such as variability in energy production [2], challenges related to limited materials for energy storage [3], and region-specific environmental impacts [4]. Consequently, there is an opportunity for the development of a *renewable energy technology* (RET) that can provide constant energy generation. *Ocean Thermal Energy Conversion* (OTEC) has been identified as a promising ocean energy technology capable of delivering such a steady renewable baseload. With a global theoretical potential exceeding 44 PWh per year, equivalent to 1.6 times the global electricity demand in 2023 [5], OTEC has undeniable potential to contribute to the global renewable energy mix.

Due to the relatively stable nature of ocean thermal energy resources, OTEC has the capability to generate a constant stream of electricity, functioning as a baseload energy source. This unique characteristic among renewable energy technologies positions OTEC as a notable option for enhancing energy security through renewable means. Additionally, OTEC plants, particularly offshore facilities, require less land compared to other RETs. The scalability of OTEC, coupled with the potential to produce useful by-products such as cold water for air conditioning [6], further underscores its versatility. Initiatives like the OTEC Bill passed in Malaysia, aimed at fostering the development of this technology, and projects like Global OTEC's planned 1.5 MW_{gross} plant in São Tomé and Príncipe [7], reflect the ongoing global interest in the technology.

Despite its potential, OTEC faces notable challenges, primarily in transitioning from the pre-commercial to the commercial phase. The largest OTEC demonstration plant to date, operated briefly by the *Korean Research Institute of Ships and Ocean Engineering* (KRISO) near Pohang, South Korea, had a capacity of 1 MW_{gross} [8]. However, the absence of an operational plant with a capacity of 2.5 MW_{gross} or more remains a critical obstacle to the technology's advancement [6]. Larger-scale plant validation is essential to build confidence in OTEC, especially given the high initial investment cost associated with OTEC projects, which poses substantial financial risk. This challenge contributes to a phenomenon called the "valley of death", where smaller pre-commercial OTEC plants are not commercially viable, yet the data they generate is essential to convince governments and financiers of the technology's feasibility given the size of its potential market [6]. Therefore, increased support and research are required to build confidence in OTEC and facilitate its advancement toward commercialisation.

1.2. Challenges faced by SIDS in the future

Although *Small Island Developing States* (SIDS) contribute less than 1% of global greenhouse gas emissions, they are home to some of the most climate-vulnerable populations globally [9]. The impacts of sea levels rising and extreme weather events pose significant threats, potentially rendering these territories uninhabitable by the end of the century without urgent mitigation efforts [9]. The gravity of this situation is highlighted by statements such as that of Barbados Prime Minister Mia Mottley, who remarked at the 26th UN Climate Summit that "A 2-degree Celsius rise in global temperature would be a death sentence for island and coastal communities", reflecting the real concern among these nations regarding their future under the current trajectory of global warming [10].

In terms of renewable energy options, many SIDS have limited access to baseload resources like hydro, geothermal or biomass. While intermittent solar and wind resources are often available, the restricted land availability on many islands constrains the development of large-scale onshore projects [11]. OTEC can be one of the few, in some cases the only, renewable baseload options available to certain SIDS.

SIDS have been identified as a high potential market for the deployment of OTEC technology [12, 13]. They are particularly well-suited for OTEC due to their unique geographic, economic and environmental characteristics. Many SIDS are located in tropical and subtropical regions with access to warm surface waters and cold *deep-sea waters* (DSW), providing the thermal gradient required for OTEC operation [13]. Economically, these islands often depend heavily on imported fossil fuels, making them vulnerable to price volatility and supply chain disruptions. OTEC could offer a renewable, locally sourced energy alternative that enhances energy security.

OTEC's environmental benefits, including low carbon emissions and minimal land use, are particularly advantageous for SIDS, which are highly vulnerable to the impacts of climate change and often have limited land resources [12]. Economically, scaling OTEC to commercial levels could provide additional benefits, such as job creation, potential cost savings on electricity compared to expensive imported fossil fuels and support for sustainable development and climate resilience.

1.3. Problem statement and research objective

As outlined in Sections 1.1 and 1.2, SIDS have demonstrated a strong interest in transitioning to renewable energy. However, they face notable challenges in this transition, including limited land availability and limited access to renewable baseload energy sources.

OTEC has been identified as a potential baseload energy source for SIDS, independent of weather conditions, that can be situated offshore, thereby minimising land use. However, despite an estimated global potential of 30 *tera-watt* (TW), only a small fraction of this capacity is currently being utilised [14]. As indicated in Section 1.1 the technology is facing problems advancing to a commercial phase. A large part of this can be attributed to insufficient funding and limited governmental support [15]. The absence of large-scale, operational OTEC plants, coupled with the lack of historical data, contributes to uncertainty regarding the true costs associated with such projects, which in turn discourages potential investors [6]. The largest OTEC plant currently in operation has a capacity of approximately 100 kW [16], whereas plants with capacities ranging from 1 MW_{gross} to 100 MW_{gross} are considered necessary for economic viability [12]. To build investor and governmental confidence, studies that employ modelling to demonstrate OTEC's potential are crucial. These models can provide a better understanding of the technology's cost competitiveness both as a standalone unit and as a component of the power system.

Aruba, the SIDS investigated in this study, was selected due to its high OTEC resource potential and its demonstrated commitment to transitioning toward a more renewable power system [17]. Furthermore, Aruba has strong economic potential, with one of the highest GDPs per capita in the region [18], and a high electricity demand [19], both of which are argued to support the deployment of commercial-scale OTEC.

The primary objective of this work is to explore the decarbonisation options available to Aruba and to evaluate fully renewable power system configurations that may be cost-effective under a diverse set of assumptions. This analysis aims to provide insights into the technical and economic feasibility of implementing OTEC in Aruba by evaluating the power system as a whole, rather than focusing on individual renewable generation technologies in isolation. Additionally, the study aims to identify the social and institutional changes required in Aruba to support the decarbonisation process, particularly in the context of integrating an emerging technology like OTEC.

By explore the technical and economic feasibility of implementing OTEC in Aruba, this work hopes to enhancing confidence in the technology and offer recommendations for its deployment, contributing to the further development of OTEC in Aruba.

1.4. Research Question

The problem statement and research objectives are encapsulated into the *main research question* (MRQ) underlying this work, namely:

Is it technically and economically feasible to implement OTEC in Aruba's energy system and if so what technical, economic and social factors play a role?

To answer this MRQ the following *sub research questions* (SRQ) are addressed:

1. What is the state of the art of OTEC's technical and economic potential and of modelling fully renewable SIDS energy systems?
2. What is the technical potential of CC floating OTEC and other renewable technologies in Aruba and how do they compare economically?
3. What are cost-effective configurations for Aruba's future renewable electricity system under varying techno-economic assumptions and scenarios and what is OTEC's role in them?
4. Who are the important stakeholders and how can they promote or obstruct OTEC's development?

1.5. Research Approach

This work employs a combination of quantitative and qualitative information-based analyses, structured into four main steps. The first two steps are grounded in quantitative data, while the third step is based on qualitative analysis. In the final step, recommendations are formulated based on the findings from the preceding quantitative and qualitative analyses.

The first step consists of a techno-economic analysis of viable RETs in Aruba, namely, OTEC, utility scale land based solar PV, offshore floating solar PV, onshore wind and fixed foundation offshore wind. This analysis evaluates the technical potential of these technologies and compares their economic competitiveness using *Geographic Information System* (GIS) tools and cost data obtained from literature. The purpose of this analysis is to provide insight into the various generation and storage technologies that could make up Aruba's power system. Additionally, it establishes the parameters and data inputs required for the subsequent step of this work.

The second step involves evaluating what future renewable power system configurations in Aruba could be cost effective under a diverse set of conditions. To do this a conceptual model of Aruba's power system is developed using modelling and simulation software. In recent years, hourly energy modelling has become increasingly important with power and energy system models integrating more variable renewable sources like wind and solar PV [20]. These models are formulated as optimisation problems to evaluate constraints such as renewable energy capacity expansion and to assess the cost-effectiveness and feasibility of the system [21]. Accordingly, this model is formulated as an optimisation model and incorporates technical and economic parameters, including *Capital expenditure* (Capex), *Operational expenditure* (Opex), electricity demand and resource availability, to evaluate various scenarios. These parameters are used to calculate the *Levelised Cost of Electricity* (LCOE) and the *Levelised Cost of the System* (LCoS). This analysis enables the assessment of system wide economics considering OTEC and other renewable energy technologies under different conditions, such as varying OTEC plant sizes, technology costs and weather patterns.

The third step focuses on evaluating the stakeholders and institutions involved in the implementation of OTEC in Aruba. Understanding the roles, interactions and influence of these stakeholders and institutions is crucial for assessing the viability of OTEC from both technical and social perspectives. Stakeholders are identified, and their interactions are mapped and summarised using the "six steps" approach outlined by Enserink et al. [22]. Additionally, a PESTEL analysis (Political, Economic, Societal, Technological, Environmental and Legal) is conducted to provide an overview of the socio-economic environment in Aruba and identify factors that could influence the successful implementation of OTEC. Finally, a strategic roadmap is developed to visualise the implementation process, offering insights into how the socio-economic environment can be navigated and optimised to support OTEC's deployment in Aruba.

Finally, based on the outcomes of the techno-economic analysis, power system model results and stakeholder and institutional analysis, the technical and economic feasibility of implementing OTEC in Aruba is evaluated. This evaluation leads to recommendations on how to enhance the likelihood of OTEC's successful implementation in Aruba.

1.6. Alignment to Sustainable Energy Technology

This research explores the implementation of OTEC, a renewable energy technology with potential to benefit climate-vulnerable SIDS and other regions. OTEC's ability to provide a renewable baseload of electricity could considerably enhance energy security of these regions by introducing a reliable domestic energy source and diversifying the electricity generation mix. Through the analysis of OTEC's technological and economic feasibility, this study seeks to contribute to the confidence in the technology's economic viability in future. This supports its advancement toward commercial deployment, where it is anticipated to deliver economic benefits, in addition to sustainable electricity. The academic contribution of this research lies in the novel integration of spatiotemporal power system modelling with stakeholder and institutional analysis, considering the technical as well as social aspects.

1.7. Thesis outline

This thesis report is divided into four parts.

Part I consists of the preliminary steps taken and encompasses chapters 2, 3 and 4. Chapter 2 presents a technological background on OTEC with a brief explanation of the technology and its history. Chapter 3 presents the literature review used to address the knowledge gaps within this field of study. Chapter 4 contains the methodology employed in this work.

Part II is made up of chapter 5 and 6. Chapter 5 presents the results for the techno-economic analysis and Chapter 6 containing the results for the power system modelling analysis.

Part III consist of Chapter 7 which describes the results of the stakeholder and institutional analysis.

Part IV includes chapter 8 and 9. Chapter 8 presents the discussions related to the results, a reflection on scientific and social relevance, and an elaboration on the limitations of this work. Chapter 9 draws conclusions from the insights gained in this work as well as providing recommendations for OTEC's implementation in Aruba, future research and the industry.

2

Theoretical Background on OTEC

This chapter presents a theoretical foundation to aid in the interpretation of this study. Firstly, the process through which OTEC generates electricity is described in Section 2.1, followed by a description of the global potential of ocean thermal energy resources in Section 2.2. Finally, an overview of the historical development and past implementations of OTEC projects is provided in Section 2.3.

2.1. Ocean Thermal Energy Conversion

Thermal ocean energy conversion produces electricity by harnessing energy from the temperature differences between ocean depths. The idea of harnessing these ocean thermal resources to generate electricity, which would come to be known as OTEC was first formally proposed back in 1881 by the french physician Jacques-Arsène d'Arsonval.

D'Arsonval proposed to use relatively warm (24-30°C) surface water to vaporise a pressurised low boiling point liquid (ammonia) through a heat exchanger (i.e. evaporator) and to use the resulting vapour to drive a turbine-generator. Subsequently, cold deep ocean water (8-4°C) transported to the surface from 800-1000m depths, would condense the ammonia vapour through another heat exchanger (i.e. condenser). The process is grounded in the thermodynamic Rankine cycle. Because the ammonia circulates in a closed loop, this concept has been named *closed-cycle OTEC* (CC-OTEC) [12]. This results in a non-intermittent or continuous source of renewable electricity. The process is illustrated in Figure 2.1.

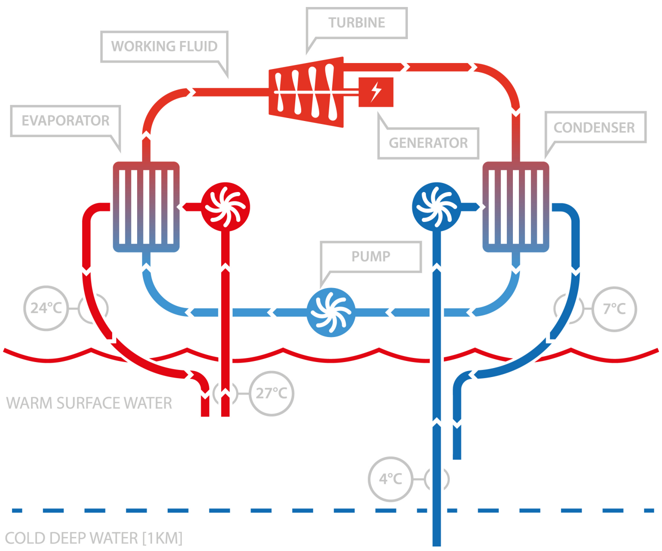


Figure 2.1: Working principle of closed cycle OTEC [23].

This process relies on the vertical temperature distribution in the open ocean. This distribution can be represented as two layers (Figure 2.2), separated by an interface. The upper layer is warmed by the sun and is mixed to depths of about 100m by wave motion. The bottom layer consists of colder water, which originates from high-latitude locations in the Atlantic such as the Labrador and Greenland Sea, as well as the Weddell Sea in the South [24]. The interface between the two layers, or thermocline, is sometimes defined by an abrupt change in temperature but in most cases the change is gradual. These two layers can be viewed as two reservoirs providing the heat source and the heat sink required for a heat engine [12].

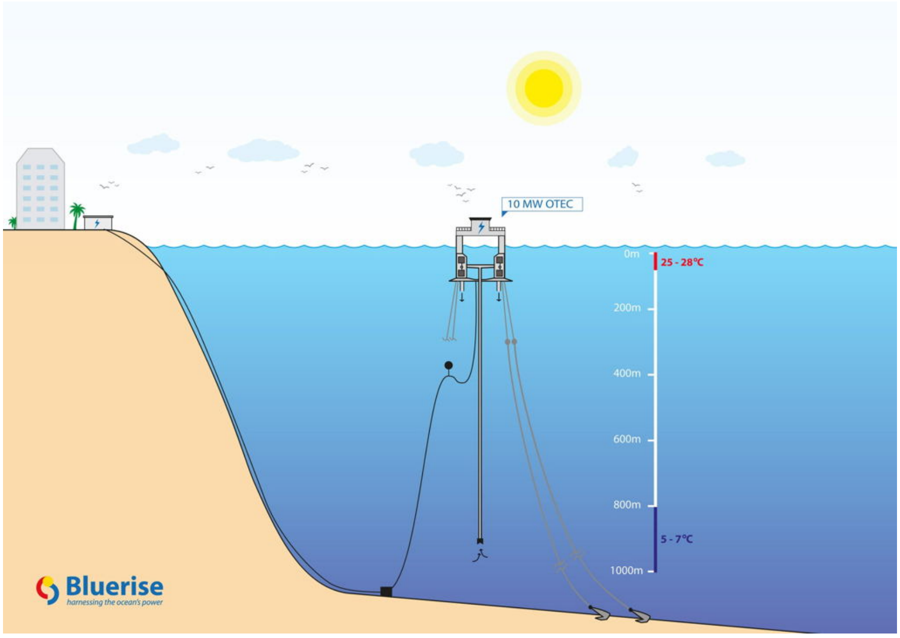


Figure 2.2: Illustration of an OTEC plant with warm layer in red and cold layer in blue [25].

Forty years later, another french inventor named Georges Claude proposed to use ocean water as a working fluid instead of ammonia [26]. In this cycle the surface water is flash-evaporated in a vacuum chamber. The low pressure steam that is created is used to drive a turbine-generator. Subsequently, cold deep ocean water is used to condense the steam after it has passed through the turbine. As a result, in addition to electricity, this cycle can be configured to produce desalinated water. Since the working liquid only flows through the system once, thereafter exiting the system, it is referred to as *open-cycle OTEC* (OC-OTEC). Combining a CC-OTEC design with an OC-OTEC design results in hybrid plants. This work focuses specifically on CC-OTEC; hence, any subsequent reference to OTEC will pertain exclusively to CC-OTEC.

Furthermore, a number of different configurations for OTEC plants have been proposed ranging from land based, including shelf mounted and other offshore structures to floating plants (Figure 2.3). The generated energy can subsequently be transported via different types of carriers such as: chemical, thermal and electrochemical. Non-electrical carriers, such as hydrogen and anhydrous ammonia, have been investigated as potential options; however, submarine power cables have been identified as the most cost-effective transmission medium for plants close to shore, as is the case for Aruba [12]. This work focuses specifically on floating, moored systems deploying submarine power cables; hence, any subsequent reference to OTEC will pertain exclusively to floating, moored plants connected to the grid with submarine power cables.

OTEC plant power output can be expressed in terms of either gross power rating [MW_{gross}], which represents the total power generated by the plant, or net power rating [MW_{net}], which accounts for the power available after subtracting the plant's internal consumption, such as the electricity used by pumps. In subsequent references in this work, the power capacity of an OTEC plant will refer to the gross power rating unless stated otherwise.

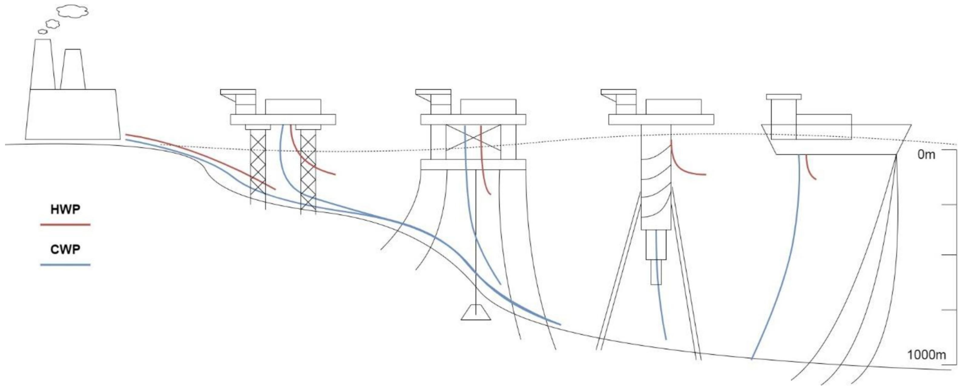


Figure 2.3: Potential configurations for OTEC plants ranging from land based to floating [16].

2.2. OTEC Resources

For OTEC to function effectively, certain oceanographic and climatic conditions must be satisfied. Most important is a temperature difference between surface and deep sea water of at least 20°C. To achieve this temperature difference access to warm surface water and cold deep sea water is essential [27]. Cold deep sea water can consistently be found at a depth of 1000 meters in the Caribbean Sea [28].

Simulations conducted in recent years have estimated a global theoretical potential of OTEC up to 30 TW [14]. Follow up studies have found technical potential varying between 3.4 and 10.0 TW [15]. Furthermore, at least 98 nations and territories have been identified as having access to ocean thermal energy resources within their 200-nautical-mile *Exclusive Economic Zone* (EEZ) [29]. The potential is highest in waters with high surface temperatures with minimal temperature fluctuations and access to sufficiently cold water [13]. Such conditions are often found at equatorial waters, between 10◦N and 10◦S, even stretching between 20◦N and 20◦S with exception of the west coast of South America, Southern and Northern Africa, the Horn of Africa and the Arabian Peninsula as shown in Figure 2.4 [16].

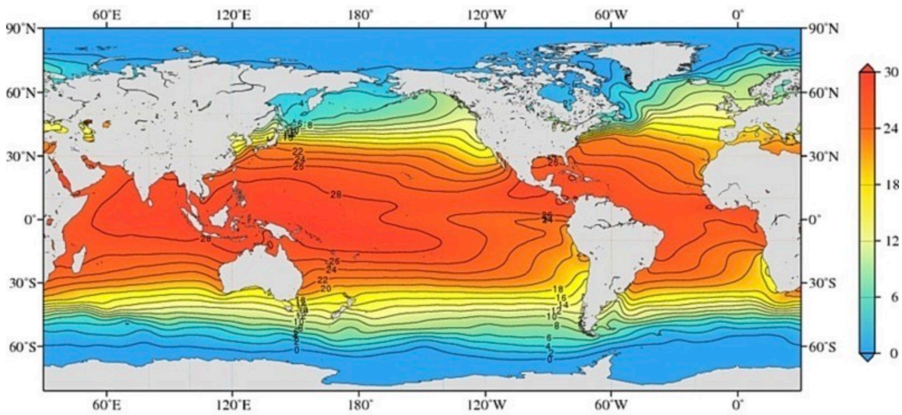


Figure 2.4: Mean annual world temperature at sea surface, for the years 2005-2017 [30].

Regions such as the Caribbean Sea, Indian Ocean (Reunion), Pacific Ocean (Hawaii), Philippines and of the coast of Africa (countries such as Tanzania and Mozambique) have been identified with high ocean thermal energy resource potential [31, 32].

The application of OTEC is particularly relevant for SIDS [33]. Many SIDS are situated within the geographical region shown in Figure 2.4, where ocean waters exhibit stable warm temperatures. These islands traditionally depend on volatile high-cost fossil fuels, such as *Heavy Fuel Oil* (HFO) and *Liquefied Natural Gas* (LNG), for electricity generation. This dependency establishes a scenario where

OTEC could emerge as not only an economically viable alternative but also a competitive energy source, offering enhanced energy security.

2.3. Current state of OTEC projects

Since D'Arsonval formally proposed OTEC as a concept there have been a number of cases where the technology was implemented, with varying degrees of success. The feasibility of the OTEC concept was demonstrated by Claude in the 1930's with the development of a 22kW pilot OC-OTEC plant [34]. After this initial demonstration OTEC did not gain much attention until the 1970/80s. As oil prices reached unprecedented levels during this period, alternative energy sources, including OTEC, were revisited and considered for development.

During this period, two notable projects were the "mini-OTEC" initiative in Hawaii (1979) [35] and Saga University's OTEC plant in Nauru, Japan (1981) [36]. The "mini-OTEC" project in Hawaii involved a 50 kW CC floating structure that utilised ammonia as the working fluid. This project successfully demonstrated the feasibility of employing a CWP with a length of 670 meters, which was connected to a mooring platform at a depth of 1370 meters. A subsequent project, "OTEC-1," developed a 1 MW plant and introduced a special motion decoupling gimbal to manage the high stresses on the CWP. Although the "OTEC-1" was planned to operate for 3 years, after a change in American administration it only operated for four months. It did however successfully validate the deployment of the primary components of an OTEC system on a large scale [6].

(a) mini-OTEC (1979) [12].

(b) OTEC-1 (1980s) [6].

Figure 2.5: Photos of the mini-OTEC and OTEC-1 facilities.

The Japan based projects consisted of multiple 100kW or less land based CC-OTEC plants from Saga University which operated successfully. The projects aimed to test the load response characteristics, turbine and heat exchanger performance. This achievement proved the feasibility of 100kW OTEC plants.

Following the decrease of oil prices, the number of OTEC projects declined. However, several notable projects have been undertaken since then. (1) In 2015, the American engineering firm Makai Engineering constructed the first CC-OTEC plant to be connected to the U.S. electricity grid. This 105 kW demonstration plant is capable of supplying power to approximately 120 homes. While it is reported to still be operational, there is no publicly available data on its performance in literature. (2) In 2013/2016, Okinawa Prefecture in Japan established a 100 kW OTEC demonstration facility with technical assistance from Saga University, subcontracted to IHI Plant Construction, Yokogawa Electric and Xenesys Inc, which is still operational. (3) KRISO developed the K-OTEC 1000 (Figure 2.6), a 1 MW barge, which successfully completed a trial operation in 2022 with an output of 338 kW [8]. These projects highlight ongoing efforts to advance OTEC technology despite the overall reduction in project activity following the decline in oil prices.

Figure 2.6: KRISO's 1-MW K-OTEC 1000 barge [8].

A summary of key OTEC research and development projects is presented in Table 2.1.

Table 2.1: Summary of key OTEC research and development projects, adapted from [6].

Agency/company (Country)	Year, Location	Gross Power Rating (kW)	Net Power Rating (kW)
Claude (France)	1930, Cuba	22	n.a.
Mini OTEC (US)	1979, Hawaii	53	18
OTEC-1 (US)	1980, Hawaii	1000	n.a.
Toshiba & TEPC (Japan)	1982, Nauru	120	31.5
Saga University (Japan)	1984, Saga	75	n.a.
NELHA (US) Open Cycle	1992, Hawaii	210	100
Saga University (Japan)	1995, Saga	9	n.a.
NELHA (US)	1996, Hawaii	50	n.a.
NIOT (India)	2000, Tuticorin (incomplete)	1000	n.a.
Naval Group (France)	2012 onwards, La Reunion	15	n.a.
KRISO (South Korea)	2012, Goseong	20	n.a.
Okinawa Prefectural Government (Japan)	2013/2016, Kumejima	100	n.a.
Makai Ocean Engineering (US)	2015, Kona, Hawaii	100	n.a.
K-OTEC1000 Barge, KRISO (South Korea)	2019, Floating unit	1000	338
SATREPS Hybrid OTEC pilot plant (Malaysia)	2019, Port Dickson	3	n.a

3

Literature Review

To assess the state of the art of OTEC's technical and economic potential and modelling fully renewable SIDS energy systems (sub question 1), a literature review is conducted. The search methodology employed for this review is described in Section 3.1. Subsequently, the results of the review and identified knowledge gaps are presented in Section 3.2.

3.1. Literature Search Methodology

To acquire an understanding of the current academic state of the art on OTEC and renewable energy system modelling on Aruba and other SIDS, the following search method was conducted. Relevant scientific articles were examined by employing the search engines Scopus and Google Scholar and sorting the results by relevance. Additionally, backward searching was applied with two iteration cycles. Lastly, papers recommended by others were taken into consideration as well.

Apart from papers in peer-reviewed journals, publications such as non-peer reviewed conference papers, industry reports, master theses and publications by companies associated with OTEC have also been considered due to the limited peer reviewed literature on topics such as economic and financial data on OTEC. Here close attention is paid to the validity of their contents by cross-examining relevant data and investigating cited sources.

An overview of the search queries and keywords is presented in Figure 3.1.

Search Code	**Database**	**Search query**	**Number of publications**	
			Before Selection	***After Selection***
ST1	Scopus	TITLE-ABS-KEY((otec OR "ocean thermal energy conversion") AND (energy) AND (resource OR practicable OR theor* OR techn* OR econom*) AND (potential))	187	10
ST2	Scopus	(otec OR "ocean thermal energy conversion") AND (caribbean OR aruba OR antilles)	130	6
ST3	Scopus	(renewable OR wind OR solar) AND (energy) AND (resource OR practicable OR theor* OR techn* OR econom*) AND (potential)) AND (Aruba)	108	3
ST4	Scopus	TITLE-ABS-KEY("renewable energy" AND system AND (fully OR full OR 100) AND (island OR islands))	454	4
ST5	Scopus	TITLE-ABS-KEY(dunkelflaute OR "anticyclonic gloom" OR "dark doldrums" OR "dark wind lull")	21	3
Backward				3
Gray Lit.				3
Total				32

Figure 3.1: A summary of academic literature search methodology and queries.

The selection was made with the following criteria. To ensure the articles in this review are relevant and up to date with the fast-developing current literature, papers from before 2014 are excluded. An exception is made however for the literature search for OTEC due to the limited available literature on OTEC regarding economic feasibility, here literature from 2000 onward is included. For the literature review on OTEC the focus was aimed at articles discussing; the historic development of OTEC and technical and economic feasibility of OTEC with indicators such as power resource potential, net power, component cost estimations, LCOE and technically limiting components.

3.2. Literature Review Results and Knowledge Gaps

Section 3.2.1 presents the results of the literature review, supplemented by Tables 3.1 and 3.2, which provide an overview of ten selected papers that were reviewed. These tables summarise the primary findings, including the key contributions and recommendations of each study. Based on these results, the subsequent Section 3.2.2 identifies and discusses the knowledge gaps revealed through the review.

3.2.1. Literature Review Results

The first key finding pertains to the current technical and economic state of OTEC. The technology is in a pre-commercial phase, with deployed plants ranging from a few kilowatts to 1 MW [16, 37, 6]. To advance OTEC to a commercial phase, considerable investments in the development and construction of larger plants are necessary. Several companies are actively working on the development of commercial-scale CC floating plants, such as Global OTEC and Makai Engineering[38, 7]. It is reported that 10-50 MW floating, CC-OTEC facilities are technically feasible using current design, manufacturing, deployment techniques and materials [39, 40, 41]. Moreover, further investigation is needed to understand the implications of the large volumes of discharge water associated with OTEC plants with capacities exceeding 100 MW [39]. Plants ranging from 20 MW to 100 MW, have been proposed in literature, including a 20 MW plant [42], a 53.5 MW plant [33], a 75 MW plant [43] and 100 MW plants [44, 45]. It is expected that experience gained from constructing smaller commercial plants (1-10 MW) will be beneficial in optimising technical aspects associated with scaling up, particularly concerning components such as the CWP [46, 12], heat exchangers [47], turbines [48], thermodynamic cycles [49, 50, 51], working fluids [52, 53] and platform and mooring systems [54]. Furthermore, a study by Langer & Blok [13] analysed more than 100 regions with technically feasible sites, identifying locations where the LCOE for commercial OTEC plants could be below \$0.15 (2021)/kWh. This is higher than for other major RETs, a decline in cost is therefore important for the technology to become cost competitive in the future. However, in the short to medium term, SIDS have been identified as a relevant niche market for OTEC due to their access to warm sea surface water and their reliance on high-cost fossil fuel electricity generation [12]. SIDS represent a strategically advantageous entry point for the development and deployment of OTEC technology. By initially focusing on these regions, it is possible to achieve cost reductions and enhance the economic competitiveness of OTEC, thereby facilitating its broader adoption in the future.

The second key finding highlights that while numerous published studies have investigated the feasibility of OTEC on islands such as Réunion [55, 56], San Andrés [57, 58], the Maldives [59], Barbados [60] and Mauritius [61], as well as in countries and larger territories including the United States (Florida) [62], Mexico [63], Indonesia [27, 64], Bangladesh [65], India [66], the South China Sea [67] and the Oman Sea [68], there remain notable gaps in literature. These studies often focus on factors such as plant siting locations, efficiencies and LCOE. However, critical aspects such as cost reductions through economies of scale, the influence of local electricity demand, location-specific variables (e.g. seasonal sea temperature variations) on net power output and the impact of financial factors like interest rates are frequently overlooked. Moreover, although the Caribbean has been identified as having high ocean thermal energy potential [69], specific regions, particularly the Lesser Antilles, have been understudied. Notably, there is an absence of research examining the feasibility and potential for OTEC implementation in Aruba and the other regional *Aruba, Bonaire and Curacao* (ABC) islands. Two master theses, by Acevedo (2016) [70] and van Velzen (2017) [71], were found addressing Aruba's transition to renewable energy, including OTEC. However these works do not primarily focus on OTEC, nor do they differentiate between onshore and offshore wind energy or consider the integration of more recently developed technologies such as floating PV systems. Additionally, the various stakeholders involved in the potential implementation of OTEC technology on the island are not explored in these analyses.

It is also worth noting that the company Bluerise has investigated OTEC opportunities in Aruba [72], yet comprehensive research in this area remains limited.

The third finding is related to the published literature on renewable energy resources in the Caribbean and Aruba. It is found that research on renewable energy resources in the Caribbean island group Lesser Antilles, where Aruba is situated, is sparse, with a limited number of published works focusing on solar and wind energy resources. Four works were found that included Aruba; firstly, a study conducted by Chadee et al. (2014) [73], which provides a high level overview of wind energy potential in the Caribbean including Aruba within the Lesser Antilles. Furthermore, work from Brendel et al (2020) [74], investigates renewable resources in Aruba to power a desalination plant using wind and solar energy resources. Thirdly, a study from Dominković et al. (2018) [75] was found investigating the integration of high shares of variable renewable energy sources for a Caribbean Island with data based on Aruba. However, this analysis only includes wind and solar resources with no differentiation being made between on and offshore applications. Lastly, work from Brecha et al. (2021) [76] investigates the potential of OTEC in the Caribbean, where Aruba is mentioned but not included in the more detailed analysis. In addition, none of these works explore a fully renewable energy system.

The fourth finding is related to literature on fully renewable energy systems on islands, with a primary focus on modelling studies. It is observed that OTEC's role in fully renewable island energy systems is largely not considered in published research. Only two geographical locations were found where OTEC was included in the renewable system analysis; La Réunion by Selosse et al. [56], Drouineau et al. [77] and Bouckaert et al [78] and Indonesia by Langer et al. [79]. The large majority of research focuses instead on wind energy, solar energy, battery storage and, where applicable, hydro storage and geothermal energy [80, 81, 82]. Furthermore, it is found and subsequently verified in Meschede et al. (2022) [11] that only a limited number of assessments evaluating 100% RES possibilities are carried out for islands in the Caribbean, and no such studies exist for Aruba. Additionally, it is noted that in the reviewed energy system studies social aspects, including stakeholder engagement and public acceptance, are often poorly addressed. Aspects such as stakeholders or institutions that would be necessary for the implementation of RETs on SIDS are often not considered. Observing grey literature research, work from Croes (2022) [83] takes a deeper dive into the implementation of more RETs in Aruba to facilitate the energy transition with an in depth stakeholder and institutional analysis but also omits OTEC as a potential energy source.

The fifth finding is related to published literature on the "dunkelflaute" phenomenon; a period with a sustained reduction of intermittent or non-dispatchable resources, such as wind and solar power [84]. Recent work from Sabovčik et al. [85] and Jing et al. [86] considers dunkelflaute in Europe. Furthermore, Ruhnau et al [87], investigate the necessary battery requirements for the analysed dunkelflaute in Germany. Limited work is however found considering the effects of dunkelflaute on a fully renewable system especially on SIDS which are not connected to a large electricity grid and therefore are more vulnerable to local dunkelflaute.

Table 3.1: Key findings and recommendations from studies on OTEC and RE systems (Part 1).

Author	Year	Key Contributions	Recommendations
Aresti et al. [16]	2023	Comprehensive review of OTEC systems, technological status and potential. Detailing barriers and technical limitations.	• Securing more funding opportunities for OTEC. • Improving the thermal efficiency. • Pilot studies to provide reliable data.
Langer et al. [13]	2023	Offers first global estimation of OTEC's economic potential, highlighting key factors for optimising OTEC plant design and costs.	• Detailed regional studies and pilot projects to refine the economic models. • SIDS could serve as a practical niche market for early OTEC deployment. • Encourages the integration of OTEC into global energy transition models.
Nihous et al. [88]	2008	Overview of OTEC technology, focusing on the fundamental principles, technical challenges and potential future developments.	• Strong commitment from governments and public funding. • Pilot plants to gain operational experience and reduce investor risk. • Initially focus on niche markets such as SIDS.
Herrera et al. [58]	2022	Economic feasibility study of OTEC on San Andrés Island, considers both technical and economic aspects.	• Studies on installation and mooring costs. • Potable water production as part of the plant's operation.
Langer et al. [15]	2020	Comprehensive review of the current economic assessments of OTEC, identifying several knowledge gaps in literature and proposes a research agenda addressing these gaps.	• Expanding economic analyses to include spatial levels, such as regional and global assessments. • Incorporating external natural conditions more thoroughly in economic analyses. • Use of more comprehensive economic assessment tools.
Nihous et al. [14]	2013	Assessment of global OTEC resources, with a maximum estimated annual net power production of about 30 TW.	• Refinement of the simulations, by improving grid resolution, model parameterisation and coupling between the ocean and atmosphere. • Explore more realistic scenarios for the development of OTEC resources.
Bleckinger et al. [89]	2016	Global overview of the potential for integrating RES on small islands, highlighting cost and GHG emissions reductions achieved by replacing diesel-based power systems with these hybrid renewable energy systems.	• Implementation of policies to facilitate the adoption of RET on small islands. • Financing mechanisms to overcome RETs high initial costs on small islands.
Brendel et al. [74]	2020	Comprehensive model integrating wind, solar PV and solar thermal, with desalination technologies. Demonstrating the economic viability of various renewable energy-driven desalination systems in Aruba.	• Subsidising renewable energy-driven desalination projects. • Including more detailed data on water storage capacity and electricity pricing. • Hybrid renewable energy systems.

Table 3.2: Key findings and recommendations from studies on OTEC and RE systems (Part 2).

Author	Year	Key Contributions	Recommendations
Meschede et al. [11]	2022	Comprehensive review of 100% renewable energy (RES) scenarios on islands, identifying the dominant role of solar PV and wind energy in island energy systems and highlights the challenges islands face due to limited land resources.	• Further research focusing on developing region-specific transition pathways. • More attention to the social and economic aspects of transitioning to 100% RES, including stakeholder engagement and policy frameworks. • High-resolution modelling tools to capture the complex interactions between different energy sectors and the impact of geographical and climatic conditions.
Sabovčík et al. [85]	2024	Provides a novel analysis of dunkelflaute events, using real-generation European data rather than meteorological simulations.	• Further research into storage solutions and backup systems that can address the challenges posed by dunkelflaute events. • Use of high-resolution, real-time data to improve the accuracy of renewable energy planning.

3.2.2. Knowledge Gaps

Reviewing existing literature on OTEC and renewable energy systems on islands reveals several knowledge gaps.

Firstly, there is limited research exploring OTEC as part of a fully renewable power system for SIDS. Most studies assess OTEC from a standalone techno-economic perspective, rather than considering its role within a broader power system. An important aspect of this analysis is evaluating the impact of OTEC as a baseload on overall system costs when integrated with other RETs, such as solar and wind, and comparing this to systems that rely on intermittent sources and energy storage technologies.

Secondly, there is very limited research on Aruba's capacity to establish a fully renewable energy system utilising its indigenous renewable energy resources, with a particular focus on the potential role that OTEC could play within this system. Understanding how OTEC could be effectively integrated into Aruba's renewable energy system remains an unexplored area.

Thirdly, current studies on renewable energy system models for islands and OTEC largely overlook the involvement of local stakeholders, as well as the economic and institutional contexts of the island. This gap highlights the need for research that connects technical assessments with local socio-economic and institutional environments, which are critical for the successful implementation and operation of OTEC systems.

Finally, there is a lack of research on the impact of dunkelflaute on renewable island energy systems and how these periods highlight the advantages of implementing baseload renewable energy technologies like OTEC. Gaining a deeper understanding of the implications of dunkelflaute on the stability and reliability of island energy systems, and assessing the role OTEC may play in addressing these challenges, could be valuable in improving system resilience.

This study aims to address these knowledge gaps by conducting a techno-economic analysis of RETs applicable to Aruba, followed by power system modelling to identify cost-effective RETs within the context of Aruba's power system. The analysis includes an exploration of the impact of dunkelflaute and the potential role of OTEC in a fully renewable power system for Aruba. Additionally, the involvement of local stakeholders and institutions is examined to assess their influence on the implementation of a new technologies such as OTEC.

The methodology employed for this approach is detailed in the following chapter.

4

Methodology

In this chapter the methodologies used in this work are described. Section 4.1 described the methodology for the techno-economic feasibility analysis. This analysis focuses on identifying RETs suitable for Aruba and evaluating their techno-economic potential. Subsequently, in Section 4.2 the approach for the power system modelling is outlined. Within this framework, the RETs identified through the techno-economic analysis are integrated into the model to explore cost efficient future renewable system configurations under various scenarios. Finally, in Section 4.3 the methodology for the stakeholder and institutional analysis is described.

4.1. Techno-economic Analysis

To address which RETs are technically viable on Aruba and to assess their technical and economic potential (sub question 2), a techno-economic analysis is conducted. This analysis begins by identifying and assessing RETs suitable for deployment in Aruba. It then proceeds with a technical analysis to investigate the technical potential for each technology using GIS analysis. Finally, the technologies are economically compared using the concept of LCOE to determine their cost-effectiveness.

The results obtained from this analysis are subsequently used as inputs for the power system model detailed in Section 4.2.

4.1.1. Assessment of RETs applicable in Aruba

To identify RETs suitable for implementation in Aruba, an initial collection of RETs is derived from various sources, including work by Ang et al. [90] and reports from the International Energy Agency [91], the International Renewable Energy Agency [92] and the National Renewable Energy Laboratory [93, 94]. This process generates a preliminary list of potential RETs to be evaluated for application in Aruba.

Subsequently, the renewable generation technologies are evaluated to ascertain whether Aruba possesses the necessary natural resources for their deployment, using various GIS tools and existing studies. Additionally, practical considerations, such as the scalability of the technology to meet Aruba's energy demand, assessing whether it can be configured at sufficiently small or large scales, are taken into consideration.

Furthermore, storage technologies are evaluated to identify suitable options for Aruba, drawing on reports from the International Energy Agency [95] and studies by Amir et al. [96] and Denholm et al. [97]. This analysis takes into account the geographic constraints specific to Aruba.

4.1.2. Technical Analysis

To assess the technical potential of applicable RETs in Aruba, a technical analysis is conducted incorporating GIS analysis. This analysis investigates the

- Availability of the renewable resources

- Potential capacity that can be installed
- Temporal distribution of the renewable resources
- Optimal locations for each technology

These insights are subsequently integrated into the power system model discussed later in Section 4.2.

Availability Renewable Energy Resources

To evaluate the availability of renewable resources in Aruba various GIS tools and desk research are used. For OTEC the E.U. Copernicus Marine Service's "Global Ocean Physics Analysis and Forecast" tool was utilised in combination with desk research. For solar energy and wind energy, the Global Wind Atlas and the Global Solar Atlas, were employed to assess wind and solar resources, respectively. These tools and the approach taken when employing them in this work are detailed in the sections below.

The **Global Ocean Physics Analysis and Forecast** tool includes daily and monthly mean files of temperature, salinity, currents, sea level, mixed layer depth and ice parameters from the top to the bottom over the global ocean. It also includes hourly mean surface fields for sea level height, temperature and currents. The global ocean output files are displayed with a 1/12 degree horizontal resolution with regular longitude/latitude equirectangular projection [28].

The **Global Wind Atlas** [98] is a web-based application that provides a high resolution global interactive map of wind resources. The application enables the analysis of spacial geographic data, including mean wind speeds, mean wind power densities, bathymetry and calculated capacity factors for IEC Classes I, II and III at heights ranging from 10 to 200 meters above ground or sea level. It utilises wind resource data from Vortex [99] to carry out a global mesoscale modelling simulation at 3km resolution, forced with ERA5 reanalysis data, with offshore coverage up to 200km from the shoreline.

For this analysis the application is utilised to examine Aruba's wind resources on and surrounding the island such as (mean) wind speed and (mean) wind power density. Furthermore it is used to observe the bathymetry for offshore technologies such as OTEC and offshore wind.

The **Global Solar Atlas** [100] is a web-based application that offers a high-resolution global interactive map detailing daily and annual solar resources. This application leverages solar resource data from Solargis [101]. It provides data on PV Electricity Output, Global Horizontal Irradiation, Diffuse Horizontal Irradiation and Direct Normal Irradiation at a spatial resolution of $2.5e^{-3}$ to $8.3e^{-3}$ degrees. Additionally, it suggests the optimum inclination in degrees for both fixed and tracking panels. Data sets employed in the application are sourced from the World Bank, Solargis and ERA-5.

For this analysis the application is employed to examine the rate of PV electricity output, Global Horizontal Irradiation and the optimal panel tilt angle on Aruba.

Potential capacity per generation technology

To determine the potential installed capacity [MW] for each RET in Aruba, an analysis of both onshore and offshore geographic features and the available space for RETs is conducted. In this context, 'capacity' refers to the sum of the nameplate capacities [MW] of the potential power plants, representing the maximum output they can collectively generate [102]; firstly for onshore and then for offshore technologies. The derived estimates of maximum capacity for each technology is subsequently applied as a constraint in the power system model described in Section 4.2.

In Aruba, the implementation of land-based RETs is heavily constrained by limited land availability. The island has a relatively large population and only 180 km² of land area, making it one of the most densely populated regions in the Caribbean [103]. Additionally, there is a strong emphasis on environmental conservation, with a large national park and multiple protected areas, both onshore and offshore, covering approximately 25% of the country's surface area [104], illustrated in Figure 4.1.

To assess the potential total installed capacity an approach formulated by van Zalk [105] is applied. Here power density factors [MW/km²] are used to estimate the maximum amount of potential capacity per technology based on the spatial extent of power generation. The power density factors are derived from literature for both utility based solar PV and onshore wind turbines. The potential capacity per technology is calculated by multiplying the power density factor with the estimated available land.

(a) Protected onshore area on Aruba, marked in green [106].

(b) Protected wetlands area on Aruba, marked in light blue [107].

Figure 4.1: Protected land and wetlands areas in Aruba.

To estimate the land available for RETs, the areas occupied by urban development and protected zones are analysed. To estimate the urban land area [km²] an area calculator is employed to estimate urban spatial coverage [108]. The onshore protected area is documented to encompass 34 km² [109]. It is assumed that 10% of the remaining land could be utilised for RET installations based on recent work from TNO [110]. The effect of increasing and decreasing the assumed land availability is explored in the power system model Section 4.2.2.

To assess the technical capacity of offshore RETs around Aruba, an analysis of the surrounding marine geography, particularly the bathymetry, is undertaken using the Global Wind Atlas. This examination is necessary to determine suitable areas for technologies based on sea depth. For instance, areas where the sea depth does not exceed 60 meters are suitable for fixed support monopile wind turbines [111] and shallow regions are preferable for economically installing mooring lines for floating PV systems. Additionally, Aruba's EEZ is evaluated to assess the available area for offshore RET installations. The potential capacity for each technology is calculated by applying power density factors, sourced from relevant literature, to the identified suitable sea areas.

Temporal Distribution of Renewable Resources

To evaluate the temporal variability of renewable resources on Aruba, an analysis of hourly capacity factors is conducted. These capacity factors are employed to analyse the temporal fluctuations in resource availability and are subsequently implemented in the power system model.

Capacity factors for wind and solar energy are derived from Renewables.ninja, a web-based tool that models the hourly power output using three decades of weather data from global reanalysis models and satellite observations [112]. To analyse the ocean thermal energy resources over time pyOTEC, a novel model that designs offshore OTEC plants for the best economic performance considering spatiotemporally specific availability and seasonality of ocean thermal energy resources [13], is employed. Detailed descriptions of both Renewables.ninja and pyOTEC, along with their applications in this research, are provided below.

Renewables.ninja calculates hourly power output based on global weather data and user-specified inputs for a chosen year and location. Input parameters for wind include turbine capacity, hub height and model type, while solar parameters consist of system losses, tracking capabilities and panel orientation. Furthermore, Renewables.ninja facilitates analyses per country or for a specific location "point". As Aruba is not included in the country database, location-specific analyses are employed. The configurations used in this work are summarised in Table 4.1.

Table 4.1: Configuration used for Renewables.ninja.

Type	Year	Capacity [kW]			
Wind			**Hub Height [m]**	**Turbine Model**	-
Onshore	2013	1	105	Vestas V90 2000	-
Offshore	2013	1	105	SWT 2.3 93	-
Solar			**System Loss [%]**	**Tracking**	**Tilt & Azimuth [°]**
Land Based	2013	1	10	None	14° & 180°
Floating	2013	1	10	None	14° & 180°

Renewables.ninja incorporates 33 years of weather data spanning from 1980-2023. The year 2013 is analysed in more detail, as its annual wind and solar capacity factor comes closest to the average annual wind and solar capacity factor of the 33-year dataset. Additionally, to analyse the long term trends the average capacity factor per hour of the entire dataset are plotted and analysed.

The capacity for each technology is set to 1kW as the resulting computed power output [kW] is then equal to the technologies capacity factor. This is done to reduce the steps needed to obtain the capacity factor, which will be deployed as input for the power system model later on.

For onshore wind energy the Vader Piet wind farm, the sole operational wind farm in Aruba, is used as reference [113]. This facility operates with ten Vestas V90 3000 turbines. In addition to the Vestas V90 3000, the following wind turbine models are considered for further analysis: V90 2000, Vestas V117 4000, Siemens Gamesa SG 4.5-145, Siemens SWT 3.0-101, GE 3.8-130 and Nordex N131 3000. After an analysis of the capacity factors for each turbine model, the Vestas V90 2000 is selected due to its favourable average capacity factor and the model's established operational success on the island. The hub height is set at 105 meters, matching the height of the turbines currently used at the Vader Piet farm.

For offshore wind energy, a hub height of 105 meters is also adopted based on data from the US Office of Energy Efficiency & Renewable Energy [114]. The following turbine models are evaluated: Siemens SWT 3.6-120, Siemens SWT 2.3-93, Vestas V164 8000, Siemens SWT 3.6-107, REpower 5M, Vestas V164 9500, Vestas V90 3000 and REpower 6M. The Siemens SWT 3.6-120 is selected based on its superior capacity factor and proven offshore performance [115].

For land-based utility-scale solar PV, a system loss factor of 10% is applied, consistent with values reported in literature [116, 117]. Based on findings from Bolinger et al. [118], fixed-tilt solar panels are chosen due to their higher power and energy density, a critical consideration given Aruba's limited land availability. The tilt angle is set at 14° and the azimuth at 180°, which are identified as the optimal configuration according to the Global Solar Atlas.

For floating solar PV, a system loss factor of 10% is applied [1]. While floating solar systems benefit from increased efficiency due to the cooling effect of water [119], they are also expected to experience higher rates of soiling from bird droppings and sea salt [120]. Additionally, floating solar PV systems experience higher losses due to spectral mismatch, where the panels have different angles of incidence due to wave motion [121] and transmission losses from the offshore plant to shore [122]. The tilt and azimuth angles are maintained at 14° and 180°, respectively, in line with the optimal configuration for land-based solar PV systems.

[1] Following the greenlight, it was discovered that FPV might experience higher system losses due to spectral mismatch and transmission losses to shore. Although the impact of these higher losses appear minor, they could not be fully integrated into the results section due to time constraints before the defence; instead, they are addressed in this footnote. The main implications identified are: 1) the reference and alternative scenarios remain largely unaffected, except for three alternative scenarios; 0 MW OTEC capacity and 10 MW OTEC plants (with and without subsidies). Here the deployment of FPV leads to higher total system costs, 2) the viable economic size of an OTEC plant in a 100% renewable system decreases from 35 MW to 20 MW, and 3) OTEC could be developed in Aruba earlier than outlined in the current roadmap, as an OTEC plant with a capacity of less than 40 MW would then also be viable.

pyOTEC is a novel Python-based, open source model that designs closed cycled, floating, moored OTEC plants for the best economic performance considering the spatiotemporally specific availability and seasonality of ocean thermal energy resources [13]. The model uses 1 year of daily seawater temperature data in 1/12° × 1/12° (≈ 9 km × 9 km) resolution obtained from the Global Ocean Physics Reanalysis by Copernicus Marine Service [123]. The user can define an area of interest and the size of the OTEC plant in kW. For this work Aruba is chosen with a plant size of 136MW$_{gross}$ for the reference scenario.

pyOTEC is employed to identify optimal locations for the placement of an OTEC plant and to simulate the daily net power output various OTEC plant sizes. This daily net power data is used to calculate the daily capacity factor, which is then used to assess the temporal distribution of ocean thermal energy resources near Aruba. Additionally, pyOTEC is applied to calculate the Capex and Opex estimates for OTEC plants of varying capacities used in the economic analysis described in 4.1.3. The resulting daily capacity factor profile and cost assumptions are subsequently also integrated into the power system model described in 4.2 as input parameters. A more detailed description of pyOTEC is provided in Appendix A. Further details can be found in Langer & Blok [13]

Storage Technology

This analysis aims to determine the required storage capacity for a *Battery Energy Storage System* (BESS) to support an electricity system in Aruba powered entirely by either wind or solar energy. A more comprehensive integration of both wind and solar resources is explored through power system modelling, as detailed in Chapter 4.2.

Initially technical reports from IEA [95] and work from Njema et al and Deng et al [124, 125] are reviewed to evaluate the current technological advancements in BESS. Following this, the batteries are sized using battery parameters described in Deng et al. The approach taken to size the batteries is described below.

Firstly the solar and wind farms are sized to meet Aruba's average annual electricity demand of 108MW [19]. This is done by dividing 108MW by the annual capacity factors for wind turbines and solar panels in Aruba, 61.4% and 18.2% respectively [112]. Based on this approach, the required wind farm capacity is approximately 176 MW, while the solar farm capacity is estimated at 593 MW.

Secondly, to assess the required BESS storage capacity [MWh] to provide storage for these farms, Aruba's electricity demand is analysed. An hourly electricity demand profile [MW] is constructed based on the profile described in Moorman (2017) [126]. The method to create this demand profile is described in more detail in Section 4.2.2. The constructed demand curve is presented in Figure 4.2.

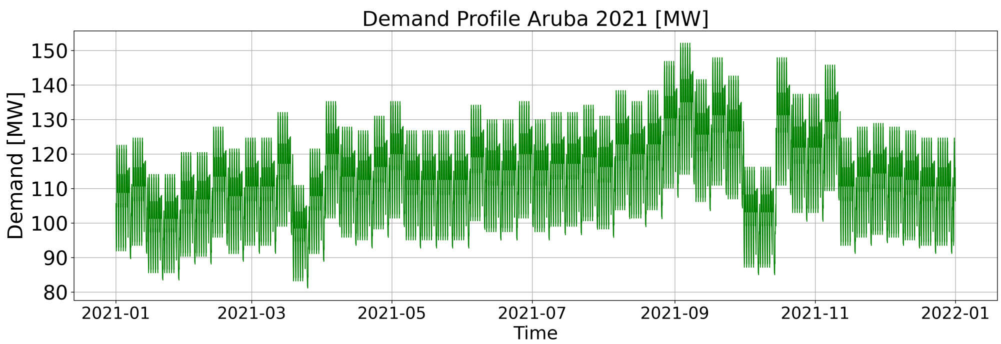


Figure 4.2: Electricity demand profile Aruba 2021.

The hourly power outputs [MW] from the wind and solar farms are derived from Renewables.ninja [112], enabling a comparison with the hourly demand profile. Subsequently, to analyse how much electricity the battery must be able to store, the hourly electricity demand [MWh] is subtracted from the hourly generated electricity from the solar and wind farms [MWh]. The resulting values are cumulatively summed over the year to create a storage profile for the BESS [MWh], which increases with electricity surpluses and decreases during deficits.

The capacities of the wind and solar farms are adjusted to ensure that the energy storage system reaches a balanced state at the end of the year, with neither surplus nor deficit energy remaining in storage. This is achieved by increasing the capacities of the wind farm to 183 MW and the solar farm to 620 MW. The required BESS capacity is then calculated by assessing the difference between the highest and lowest points on the battery storage curve.

To ensure optimal charge levels and maintain the health of the BESS, buffers are implemented as described by Deng et al. [125]. Specifically, the battery is sized to ensure that the *State of Charge* (SoC)—a measure of the available charge relative to the battery's total capacity, expressed as a percentage [127]—remains within a range of 30% to 70%, preventing excessive discharge or overcharge.

4.1.3. Economic Analysis

To assess the economic viability of various renewable energy technologies in Aruba, industry reports and scientific paper are conducted to gather data on their Capex and Opex costs. For OTEC, cost data is specifically obtained using the pyOTEC model [128]. This collected data is then utilised to calculate the LCOE for each technology.

The LCOE is a widely employed metric for assessing the economic viability of an RET. It represents the cost, averaged over the entire lifespan of a project, of generating one unit of electricity [MWh]. This metric is commonly used to evaluate whether a power generation project is economically feasible by indicating the minimum electricity price required to achieve a return on investment [129].

In this work, the LCOE is calculated using Equation 4.1.

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t + M_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E_t}{(1+r)^t}} \tag{4.1}$$

C = Capital expenditure [USD]
M = Maintenance and operations expenditures [USD/year]
E = Electricity produced over lifetime [MWh]
r = Discount rate [%]
t = Years
T = Lifetime of the technology [years]

Initially, the LCOE calculations are performed without storage costs. Subsequently, to demonstrate the impact of storage costs on a renewable energy system that includes intermittent sources, the LCOE is calculated with the inclusion of a BESS consisting of 155MW power capacity and 3 GWh of storage capacity.

This BESS would not be large enough to store the required electricity to facilitate a fully renewable energy system without over-sizing the solar and wind farms but serves to highlight the hidden costs of intermittent energy sources without a baseload. Alternatively, increasing the size of wind or solar farms would reduce the required storage capacity and likely lower overall system costs. The optimal size of these farms in isolation, however, is not explored further in this work.

The resulting LCOE's for each technology are then compared to each other with and without battery costs included, employing bar charts constructed with Python and the Matplotlib library.

RET Cost Analysis

Due to the limited availability of Capex and Opex costs for RETs specific to Aruba, global data was consulted. Given the rapid advancements in RET costs during recent years, only literature published from 2020 onward is considered. To identify relevant scientific literature, search engines such as Scopus and Google Scholar are utilised, employing queries "CAPEX" OR "OPEX" with "AND", followed by specific technology-related keywords including "wind", "solar OR PV", "onshore wind", "offshore wind", "utility-scale PV" or "floating PV". Additionally, technical reports from authoritative sources such as the

International Renewable Energy Agency, National Renewable Energy Laboratory, International Energy Agency and Lazard are also consulted.

For OTEC, cost data is collected using the pyOTEC model. As outlined in the previous section, this model provides estimates for both Capex and Opex for the designed OTEC plant. The Capex calculations are derived from the costs of individual plant components, while the Opex is determined based on the work of Vega (2010) [33], which suggests that Opex is approximately 3% of Capex. Furthermore, the pyOTEC model incorporates OTEC's significant economies of scale, as described by Equation A.1. Consequently, as the size of the OTEC plant increases, it becomes increasingly economically advantageous.

The impact of varying plant sizes, ranging from 10 MW to 150 MW in Aruba, on the CAPEX is depicted in Figure 4.3. For the economic analysis 40MW and 80MW plants are considered.

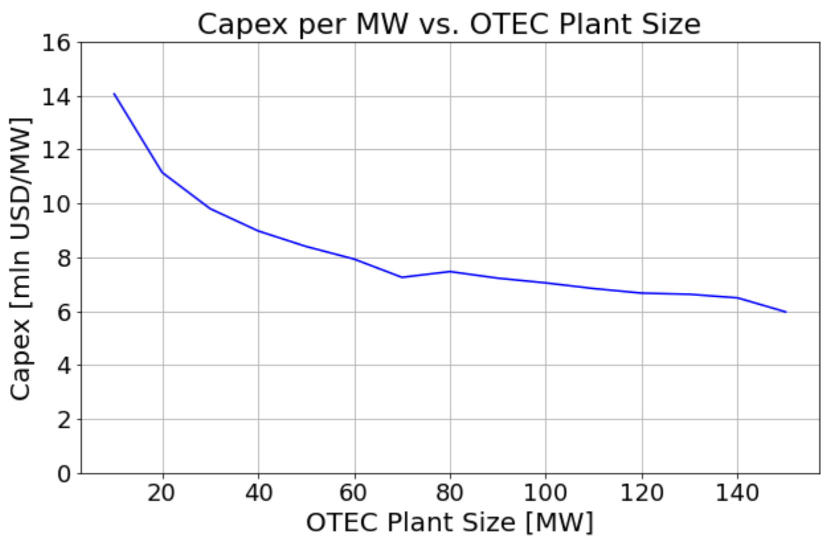


Figure 4.3: Capex of OTEC plants ranging from 10MW to 150MW retrieved from pyOTEC.

The collected data is organised and summarised in Excel. Following this, the Capex and Opex data are visualised using box-and-whisker plots generated with Python and the Matplotlib library.

4.2. Power System Modelling

To explore various decarbonisation pathways for Aruba and to consequently investigate and analyse the potential role of OTEC within these pathways (sub question 3), a power system model is utilised to model various scenarios. In this section the methodology behind this modelling approach is described. Initially, cost-optimal configurations of Aruba's renewable energy system in the years 2030, 2040 and 2050 are modelled, followed by cost-optimal configurations under various scenarios in the year 2050. Subsequently, an analysis is conducted to examine the potential role of OTEC in these configurations.

As discussed in the literature review presented in Chapter 3, prior studies such as those by Langer et al. (2024) [79], Keiner et al. (2022) [80] and Marczinkoski et al. (2019) [130] employ an *Energy System Optimisation Model* (ESOM) to simulate decarbonisation pathways across various scenarios.

Energy system models provide coherent quantitative descriptions of how energy is converted, transported and consumed in systems at various scales (Pfenninger & Pickering, 2018) [21]. By formulating the models as an optimisation problem, the impact of constraints on the system can be evaluated. These constraints can include for example limited land availability, the different costs associated with constructing and operating technologies or the elimination of fossil fuels from a country or city. By employing a modelling approach, it is possible to investigate the effects of various system interventions in a short time without affecting real-world systems. The main limitation of this approach is that the results of the model depend on assumptions and input data, which is known as the garbage in garbage out principle. This means that the quality of the output cannot be higher than the quality of the input (Nikolic et al., 2019) [131]. This limitation is addressed and to a degree mitigated by employing input data from official and scientific sources.

4.2.1. Model Description - Calliope

In this work the ESOM Calliope is employed for the power system analysis. Calliope is a flexible open source framework with which an energy system model can be built and optimised. This energy system consists of *supply technologies* such as OTEC, wind turbines or fossil fuel generators which take *resources* such as a thermal gradient, wind and fossil fuels and turns them into specific *energy carriers* such as electricity or heat. In this work only electricity is considered. Thus, the supply technologies supply electricity to the system.

This electricity is then transported through *transportation technologies* such as electrical transmission lines to *demand technologies*, such as household items and industry applications and *storage technologies* such as BESS. The demand technologies remove the energy carrier from the system.

Furthermore, Calliope can differentiate specific *locations*. Consequently, supply, demand and storage technologies can be situated in distinct geographical locations. Transportation technologies are then employed to transfer electricity between the locations of supply and those of demand and storage.

In this work, the Calliope model optimises for minimal total annualised cost. This means that the model constructs and delivers a power system, based on the provided inputs, aiming to achieve the lowest possible total annual cost. This cost represents the aggregate of all expenses incurred by the system to reliably meet the energy demand.

To assess the impacts of modifying specific constraints and inputs, various scenarios can be simulated. In this process, key inputs and parameters such as costs, demand or resource availability are altered within the model to examine their effects on the outcomes of the optimisation. This approach provides stakeholders with valuable insights into the economic, environmental and technical feasibility of energy strategies under varying conditions and constraints. In this work, the technique is applied to explore the implications of different scenarios on the implementation of OTEC in Aruba.

Calliope is a validated model extensively tested and employed within peer-reviewed research. It is designed to enable detailed analyses of systems across arbitrarily high spatial and temporal resolutions, applicable at scales varying from urban centres to national and continental levels. This versatility is achieved through its scale-agnostic mathematical framework. Additionally, the model utilises a user-friendly architecture comprising flexible, text-based building blocks for model definition, simplifying its application significantly. Similar ESOMs such as OSeMOSYS, PyPSA, TEMOA, NEMO and PandaPower [132] could also be employed. In this work, Calliope was selected due to its capability to handle analyses with high spatial and temporal resolutions, its flexibility and its straightforward usability.

The model is run with the programming language Python. Furthermore, Calliope models are defined through YAML files, which are both human-readable and computer-readable, and CSV files (a simple tabular format) for time series data. By leveraging Python's libraries, Calliope also enhances data handling, scenario analysis and result visualisation. For this work Matplotlib and Excel are employed to store and visualise the resulting datasets.

4.2.2. Model Formulation

As mentioned previously, decarbonisation pathways for Aruba and OTEC's role are explored in this work. Initially, this is done by modelling a reference scenario for the year 2050 where Aruba's energy system consists of 100% renewable technologies. Aruba is modelled using the national copperplate approach, which conceptualises the entire region as a single node. This approach assumes that all energy generation and demand occur concurrently at this centralised location. Additionally, the years 2030 and 2040 are simulated to observe the development of the generation mix in the system over time. Lastly, various scenarios are explored for the year 2050 to investigate the effect alternative scenarios have on OTEC's implementation.

As described in Section 4.2.1 the model consists of different components. These model components are presented below and described in more detail in the following section.

- Supply Technologies
- Demand Technologies
- Storage Technologies
- Transmission Technologies
- Locations
- Scenarios

Supply Technologies

The model incorporates multiple supply technologies: OTEC, onshore and offshore wind turbines, utility-scale ground-mounted and floating PV panels, diesel reciprocating engines and open-cycle gas turbines.

To simulate the supply technologies, the model evaluates several critical inputs, including costs, efficiencies, operational lifetimes and capacity limits.

Costs

In the Calliope model, costs are classified into two distinct types: monetary [USD] and emissions [kgCO^2 per MWh]. This study primarily addresses the monetary costs associated with the construction and operation of technologies. Within this framework, Calliope differentiates these monetary costs into two main categories: Capital Expenditure (Capex) and Operational & Maintenance (Opex) costs. Additionally, the model accounts for the influence of interest rates on the overall cost calculations. A detailed enumeration of these cost types is provided in Table 4.2.

Table 4.2: Cost input parameters for Calliope utilised in the model [133].

Name	**Calliope Notation**	**Unit**
Capex of energy capacity	`energy_cap`	USD/MW_{gross}
Capex of energy storage	`storage_cap`	USD/$MWh_{storage}$
Annual O&M costs (generation)	`om_annual`	USD/MW/year
Annual O&M costs (storage)	`om_annual`	USD/$MWh_{storage}$/year
Fractional annual O&M	`om_annual_investment_fraction`	% of Capex/year
Carrier production cost	`om_prod`	USD/MWh
Carrier consumption cost	`om_con`	USD/$MWh_{thermal\ eq}$
Interest rate	`interest_rate`	%

The Capex and Opex costs assumptions for each technology employed in the model are presented in Table 4.3. The costs for onshore wind, offshore wind, utility scale land-based solar and offshore floating solar are derived from estimates described in the Ministry of Energy and Mineral Resource's and Danish Energy Embassy's report on Indonesia's power sector [134], with additional cost assumptions for floating solar from Oliveira et al. (2020) [119] and TNO (2022) [135]. Capex and Opex cost assumptions from Indonesia are applied to Aruba due to several shared characteristics. Both regions are tropical island environments with similar logistical challenges, including reliance on imported renewable energy technologies, which influences transportation, installation and maintenance costs. Additionally, both operate in emerging renewable energy markets with conditions such as high financing costs.

The cost assumptions for OTEC are based on results from pyOTEC for a 136 MW_{gross} plant located off the coast of Aruba [13], with the most cost-effective plant location selected.

Table 4.3: Reference scenario Capex and Opex assumptions.

Cost Assumptions	2021	2030	2040	2050
OTEC [13]				
Capex [USD/MW]	6,549,000	5,940,000	5,412,000	4,885,000
Opex [USD/MW/year]	3% of Capex	3% of Capex	3% of Capex	3% of Capex
Onshore Wind [79]				
Capex [USD/MW]	1,660,000	1,497,000	1,412,000	1,326,000
Fixed Opex [USD/MW/year]	49,000	43,000	39,000	35,000
Var. Opex [USD/MWh/year]	0	0	0	0
Offshore Wind [79]				
Capex [USD/MW]	4,325,000	3,779,000	3,524,000	3,269,000
Fixed Opex [USD/MW/year]	20,000	17,000	15,000	13,000
Var. Opex [USD/MWh/year]	25.0	21.8	19.8	17.7
Land-based Solar [79]				
Capex [USD/MW]	1,194,000	825,000	698,000	571,000
Fixed Opex [USD/MW/year]	17,000	13,000	11,000	9,000
Var. Opex [USD/MWh/year]	0	0	0	0
Offshore Floating Solar				
Capex [USD/MW] [79]	1,497,000	1,034,000	875,000	716,000
Fixed Opex [USD/MW/year] [135]	4% of Capex	3% of Capex	2% of Capex	2% of Capex
Var. Opex [USD/MWh/year]	0	0	0	0
Battery [79]				
Capex [USD/MWhsto]	300,200	162,186	125,147	88,108
Fixed Opex [USD/MWhsto/year]	2.7% of Capex	2.7% of Capex	2.7% of Capex	2.7% of Capex
Var. Opex [USD/MWhsto/year]	0.13	0.13	0.13	0.13

Efficiency, Capacity Maximum and Lifetime

The efficiencies of the renewable technologies are accounted for in the power production profiles derived from the capacity factors as described in Section 4.1.2. Furthermore, Calliope facilitates the specification of upper limits for the capacity that can be installed for each technology, utilising the command energy_cap_max. In this work, the maximum capacity for each technology is configured with the projected maximum potential for each technology in Aruba. For a detailed explanation of how these maximum capacity potentials are calculated, please refer to Section 4.1. The operational lifetimes [years] assumed for each supply technology are presented in Table 4.4.

Table 4.4: Supply technology lifetimes and references.

Technology	Lifetime [Years]	Reference
Onshore Wind	30	[134]
Offshore Wind	30	[134]
Land-based Solar	40	[134]
Offshore Floating	25	[134]
OTEC	30	[13]

Resources

As detailed in Section 4.2.1, supply technologies convert external resources into electricity, which is subsequently supplied to the system. For conventional electricity generation, these external resources primarily consist of fossil fuels such as HFO or LNG. In contrast, RETs utilise resources such as wind, solar irradiation and thermal gradients. To quantify these renewable resources, the modeller can input hourly capacity factors, which represent the capacity factors on an hourly basis rather than on an annual basis. The model simulates a one-year period, incorporating hourly capacity factors from a specific year, which are provided in a CSV file and used as inputs for the RET resources.

As described in Section 4.1.2, to obtain the hourly capacity factor profiles used in the model two sources are consulted, Renewables.ninja and pyOTEC. Renewables.ninja is consulted for the wind and solar hourly capacity factor profiles. For the hourly capacity factor input for OTEC the Python based, open-source model pyOTEC developed by Langer et al. (2023) [13] is consulted. For descriptions of Renewables.ninja and pyOTEC please refer to Section 4.1.

Table 4.1 provides an overview of the settings used in Renewables.ninja. For pyOTEC, Aruba is selected as the country of analysis, with a system size of 136 MW.

As capacity factor profiles differ every year, data from 1980 to 2023 is analysed to find the most representable year. It is found that in 2013 the capacity factors come closest to the average values for solar PV and wind. Therefore capacity factors profiles from 2013 are used.

The capacity factor profiles of the generation technologies are presented in Figure 4.4.

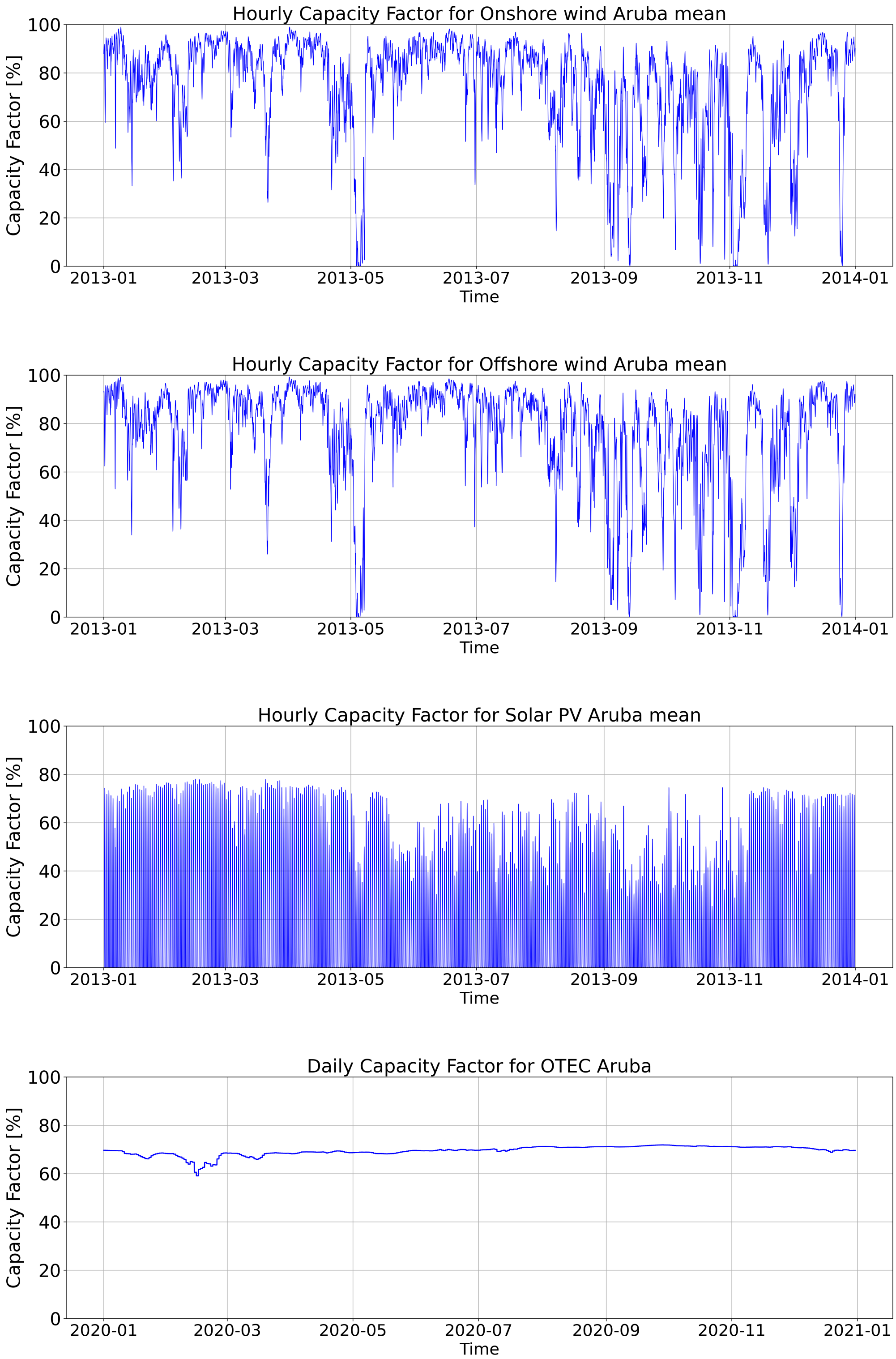


Figure 4.4: Capacity factor profiles in Aruba per RET [112][128].

Demand Technologies

The electricity demand is modelled using 1-hour time steps over a full year, with a copperplate approach applied. This means that the demand is represented as a single node, effectively centralising Aruba's total electricity demand to one geographical point.

Since no publicly available electricity demand profile exists for Aruba in 2023/24, this work utilises an earlier demand profile described by Moorman [126] (depicted in light grey in Figure 4.5). As the original source data for the demand curve is unavailable, the profile was reconstructed through visual interpretation of the provided curve.

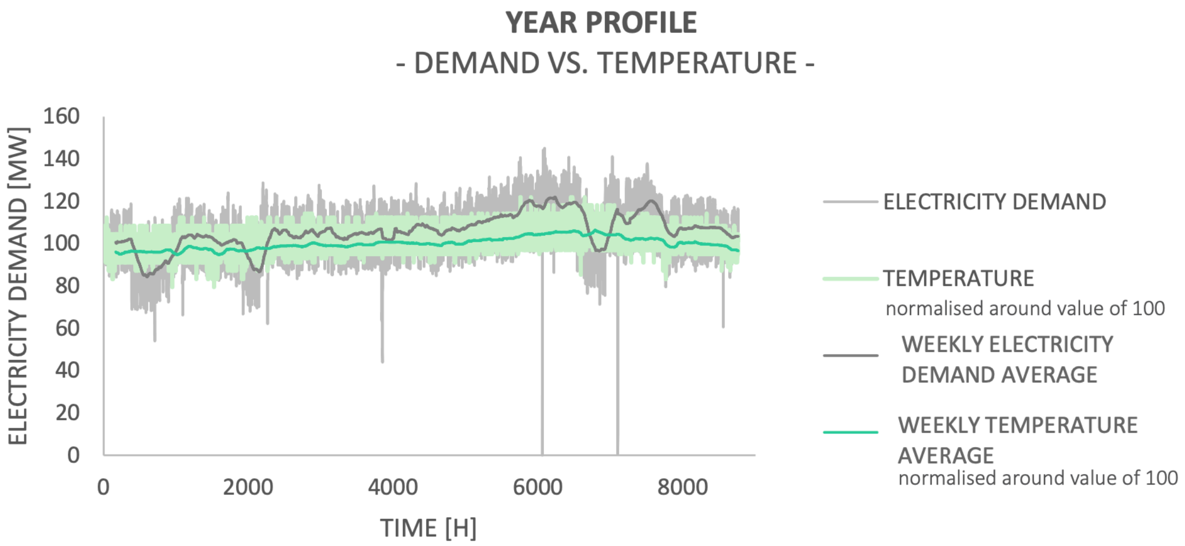


Figure 4.5: The yearly electricity demand curve presented in Moorman (2017) [126] in light gray.

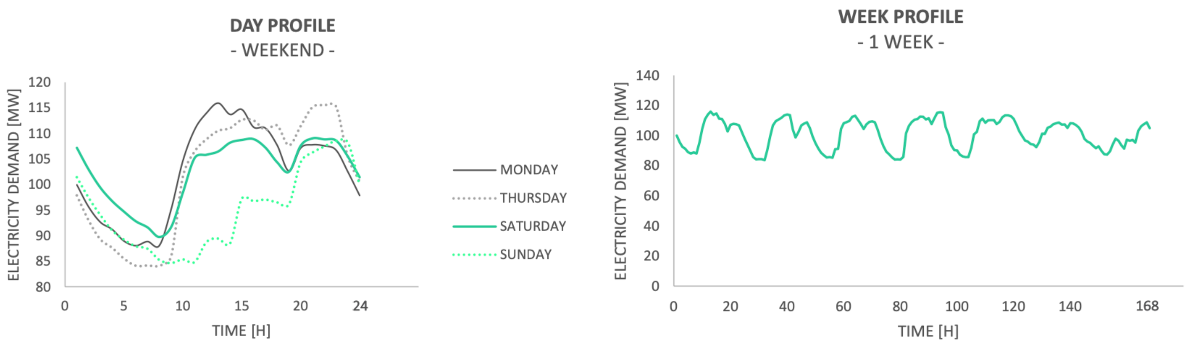


Figure 4.6: Daily and weekly electricity demand profiles presented in Moorman (2017) [126].

The visual interpretation is conducted as follows: first, a standard weekly demand profile is created based on Figure 4.6, differentiating between weekdays and weekends. Next, the annual demand profile is analysed to identify the peak demand for each week. A yearly profile is then constructed by linking 52 weekly profiles together, with each week scaled to match the peak demand identified in Moorman's annual profile. This process results in an hourly demand profile covering the entire year. The full-year profile is subsequently scaled to 2021 by applying a scaling factor based on the ratio of the total annual demand in 2021 [GWh] to the total demand of the constructed profile [GWh]. The maximum demand of the scaled 2021 curve is then compared and validated against the observed peak demand for Aruba in 2021, which is 150 MW [19].

The demand curve presented by Moorman incorporates a transmission and distribution loss of 16%, which is determined by comparing the electricity consumed by end-users (779 GWh) with the total annual electricity generation (934 GWh). These losses are reflected in the model by maintaining them within the demand profile.

The electricity demand profile from 2021 is projected forward to the years 2030, 2040 and 2050 by applying a *Compounded Annual Growth Rate* (CAGR) of 2%. This rate is determined by averaging a historical CAGR of 1.1% [136] with an anticipated CAGR of 3% forecasted by TNO [110]. Figure 4.7 shows the resulting demand curve for 2050.

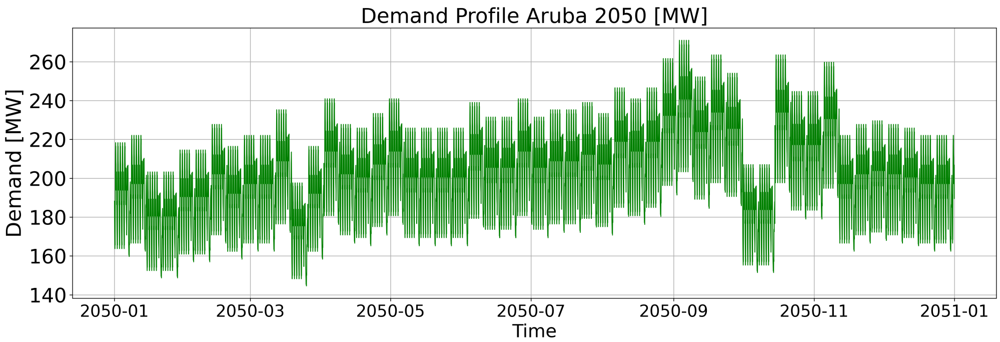


Figure 4.7: Aruba hourly demand profile 2050.

Storage Technologies

Storage technologies offer the ability to store and release electricity. This ability is especially useful for non-dispatchable technologies where the resources necessary to meet demand cannot be controlled. Additionally, it provides a buffer for unexpected increases in electricity demand aiding in supply and demand balancing. Due to Aruba's geographic landscape storage technologies such as pumped hydro are not applicable. In this work BESS is considered. The assumptions for storage are presented in Table 4.5.

Table 4.5: Assumptions for BESS storage technology.

BESS Assumptions	Value	Unit	Reference
Round trip efficiency	0.954	%	[134]
Storage losses	0.00004	%/hour	[134]
Lifetime	30	years	[79]
Interest rate	10	%	[79]
Capex	207,784	USD/MWh$_{sto}$	[79]
O&M Annual	1,710	USD/MW/year	[79]
O&M Production	1.5	USD/MWh$_{sto}$/year	[79]

Locations and transmission technologies

As previously described, Calliope facilitates the configuration of supply, storage and demand technologies at specific locations, denoted as nodes. These nodes are then connected through transmission technologies such as transmission lines. However, given Aruba's limited geographical size, the impacts of these transmission networks are considered negligible in this analysis, apart from the transmission losses, which are incorporated into the demand profile. Consequently, Aruba is modelled using a national copperplate approach, wherein the island is represented as a single node. In this model, all generation and demand occur concurrently at this singular node.

Scenarios

As previously mentioned, Calliope allows for the execution of user-defined scenarios, enabling the analysis of the effects of different input configurations. To assess the impact of these variations, alternative scenarios are developed and executed independently within the model. The input combinations for these scenarios are specified in a YAML file, allowing them to be run separately. Detailed descriptions of the scenarios and their underlying rationale are provided in the following sections, with an overview of the scenarios presented in Table 4.6.

Table 4.6: Scenario analysis with different cases and descriptions.

Nr.	Scenario	Case	Description
1	Reference	Reference	Reference Scenario 2050
2	Cost Sensitivities	Floating PV: CAPEX +20%	20% more Capex for Floating PV
3		Floating PV: CAPEX -20%	20% less Capex for Floating PV
4		OTEC: CAPEX +20%	20% more Capex for OTEC
5		OTEC: CAPEX -20%	20% less Capex for OTEC
6		Battery: CAPEX +20%	20% more Capex for Batteries
7		Battery: CAPEX -20%	20% less Capex for Batteries
8	OTEC plant Size	10MW	OTEC plant size of 10MW
9		40MW	OTEC plant size of 40MW
10		80MW	OTEC plant size of 80MW
11	Technical Limitations	Land available 5%	50% less land for Solar & Wind
12		Land available 15%	50% more land for Solar & Wind
13		OTEC Capacity 0MW	No OTEC
14	Subsidies	Subsidy 10MW plant	OTEC Capex subsidy required for 10MW
15	Fossil Fuel Phase Out	Fossil Fuels: no restrictions	No restrictions on Fossil Fuels
16		Fossil Fuels: Max 20% FF	Fossil Fuels are max. 20% of demand
17	Solar & Wind CF	Bad year (2010)	Lower CF: Solar 16.9% and Wind 48.3%
18		Good year (2015)	Higher CF: Solar 19.2% and Wind 71.2%

Cost Sensitivity

For the cost sensitivity, the Capex costs for Floating PV, OTEC and Batteries of the reference case have been adjusted by +20% and -20% and used as inputs for the Calliope model. Besides the cost of OTEC itself, the costs of Floating PV and Batteries are expected to be the most impactful on the relative ranking of OTEC and therefore these were selected for this Cost Sensitivity. Only a limited number of studies were found to describe costs as far out as 2050, hence a standard 20% deviation to the reference case has been modelled.

OTEC plant sizes

For the OTEC plant sizes scenario, the effect of different plant sizes is analysed. OTEC experiences economies of scale where the Capex per MW decreases as the plants installed capacity increases [37]. As a result larger plants become more economically viable. Additionally, technical learning is taken into account which accounts for experience gained over time, also reducing costs [79]. The different costs per plant size are presented in Table 4.7. The year 2050 is considered, so the cost assumptions from the bottom row are taken. In all cases the Opex is taken as 3% of Capex based on Vega (2012) [12].

Table 4.7: Capex per MW for different size plants over time.

Year	Reference 136MW [USD/kW]	80MW [USD/kW]	40MW [USD/kW]	10MW [USD/kW]
2021	6,549	7,472	8,980	14,060
2030	5,940	6,778	8,145	12,752
2040	5,412	6,176	7,422	11,620
2050	4,885	5,574	6,698	10,488

Technology Capacity Limitations

For the technology capacity limitations scenario, rather than the 10% land available assumed (for on-shore wind and land based solar) in the reference case, this has been changed to 5% and 15% for the first two scenarios. Also, a scenario is run without any OTEC capacity, to see what the impact on the total cost of the system and the generation mix would be in a 100% renewable scenario without OTEC.

Subsidies

Literature suggests that high investment costs are some of OTEC's highest barriers towards commercialisation, as such subsidies could provide necessary financing to attract investors. In the case of the Martinique OTEC project [92] an approximate 25% subsidy through NER300 was provided. This analysis examines the level of subsidy needed for the model to deploy a 10 MW OTEC plant. This is achieved by applying a subsidy on the Capex (in % of Capex) and incrementally increasing it until the model selects OTEC for inclusion.

Fossil Fuel Phase-out

For the fossil fuel phase-out scenario, diesel and OC-gas generation technologies are added to the model. Two scenarios are specified: 1) no fossil fuel restrictions, and 2) max 20% *fossil fuels* (FF).

In the ”No Restrictions” scenario, both gas and diesel are included without any limitations on their capacity. In the ”Max 20% FF” scenario, the capacity of OC-gas turbines is capped at 20% of the maximum demand, equivalent to 55 MW, with no diesel included. Diesel is excluded in this scenario due to its ongoing phase-out from Aruba's electricity mix, as it is unlikely to be part of a small fossil fuel energy share [137].

The assumptions used are presented in Table 4.8.

Table 4.8: Fossil fuel scenario assumptions.

Fossil Fuel Assumptions	Diesel	OC Gas	Unit	Reference
Energy efficiency	48	40	%	[134]
Lifetime	25	25	years	[134]
Interest rate	10	10	%	[134]
Capex	782	752	USD/kW	[134]
O&M Annual	9	22	USD/kW	[134]
O&M Production	6.4	4.63	USD/MWh	[134]
Fuel Cost	55.96	35.49	USD/MWh_{th}	[138]

Solar and Wind Resources

For the solar and wind resource scenarios, historical data from 1980 to 2023 was analysed, and two years were selected based on the lowest (2010) and highest (2015) solar and wind capacity factors. In the year with the lowest resource availability, the annual capacity factors were 48.3% for wind and 16.9% for solar. Conversely, in the year with the highest resource availability, the annual capacity factors were 71.2% for wind and 19.2% for solar. These scenarios represent years with extreme weather conditions, which could become more frequent in the future due to factors such as climate change.

4.2.3. Model Results Analysis

The primary results derived from the energy system optimisation include the capacities deployed [MW], annual electricity generation [GWh] and LCOE [USD/MWh] for RETs deployed in the system, as well as the *Levelised Cost of the System* (LCoS) [USD/MWh]. Particular focus is given to OTEC and its potential role across various scenarios.

The LCoS is calculated by dividing the summed levelised costs of all the deployed technologies by the summed amount electricity generated in the modelled year by all the technologies in the system. The equation is provided in equation 4.3.

$$CRF = \frac{r * (1+r)^N}{(1+r)^N - 1} \tag{4.2}$$

$CRF =$ Capital Recovery Factor
$r =$ Discount rate [%]
$N =$ Project lifetime [years]

$$LCoS = \frac{\sum_{i=1}^{N} CRF_i * Capex_i + OPEX_i}{\sum_{i=1}^{N} E_t} \tag{4.3}$$

$Capex =$ Capital Expenditure [USD]
$Opex =$ Operations & maintenance expenditures [USD/year]
$E_t =$ Annual annual electricity production [MWh/year]
$N =$ Number of technologies deployed by the model

An indicator named 'Utilisation Factor' is used to assess the extent to which deployed capacity is utilised. Observing this metric is deemed critical from an economic standpoint, as it directly influences the economic viability of an RET from a project economics perspective. The utilisation factor is defined with equation 4.4.

$$Utilisation\ Factor = \frac{E_p}{E_{max} * CF} \tag{4.4}$$

$E_p =$ Electricity supplied to the system in a year [MWh/year]
$E_{max} =$ Electricity produced in a year when operated at nameplate capacity [MWh/year]
$CF =$ Yealy Capacity Factor [%]

4.3. Stakeholder and Institutional Analysis

To find the important stakeholders and institutions and how they could enable or constrain OTEC development and implementation on Aruba (sub question 4), a stakeholder and institutional analysis is conducted.

Firstly, a stakeholder analysis is conducted to identify the entities that could either enable or constrain the implementation of OTEC in Aruba. Subsequently, the interactions among these stakeholders are examined and documented to understand the dynamics within the stakeholder network. Following this, a PESTEL analysis is carried out to identify the institutional factors that may either support or hinder the development of OTEC in Aruba. Finally, leveraging insights from the power system model, stakeholder analysis and PESTEL analysis, a roadmap is developed. This roadmap delineates a potential pathway for the future implementation of OTEC in Aruba, outlining strategic considerations and operational prerequisites.

In this section the methodology used to conduct the stakeholder and institutional analysis is described. This is done in subsection 4.3.1 for the stakeholder analysis, followed by subsection 4.3.2 for the PESTEL analysis and subsection 4.3.3 for the key stakeholders for implementation. Lastly the methodology for the roadmap is described in subsection 4.3.4.

4.3.1. Stakeholder Analysis

The objective of the stakeholder analysis is to identify key stakeholders in Aruba who have the potential to either enable or constrain the implementation of OTEC. This analysis extends beyond Aruba's energy sector, incorporating a broader socio-economic perspective that includes *non-governmental organisations* (NGOs) and local government authorities.

Previous studies, such as work by Croes (2022) [83], have identified the stakeholders within Aruba's electricity sector. Similarly, global stakeholders involved in OTEC were examined by Salz (2018) [139]. Building upon this, the stakeholder analysis incorporates additional insights, reflecting recent developments in Aruba's renewable energy transition and the advancement of OTEC on a global scale.

The methodology employed for the stakeholder analysis is based on the 'six steps' approach outlined in 'Policy Analysis of Multi-Actor Systems' by Enserink et al. (2022) [22] and the research approach of Verbong and Geels (2007) [140]. To enhance the robustness of the desk research, expert consultations were conducted with two individuals: one possessing in-depth knowledge of Aruba's electricity sector and the other an expert on OTEC and its potential implementation in Aruba. These consultations aided significantly in verifying existing research and acquiring additional, less widely known information about the stakeholders and the stakeholder network in Aruba.

The analyses method described in Policy Analysis of Multi-Actor Systems is in line with the guidelines for general stakeholder analyses. However, where stakeholder analyses typically focus on the dimensions of power and interests of actors, this method also covers the network structure and perceptions of actors. The six steps described are as follows:

1. Formulation of a problem and associated decision arena as a point of departure.
2. Identification of the actors involved.
3. Mapping the formal institutional playing field: chart the institutions and relations of actors.
4. Identifying actor characteristic: determine the interests, objectives, perceptions and resources of actors.
5. Summarising the interdependence between actors using overview tables or diagrams.
6. Determine the consequences of these findings with regard to the problem formulation.

This work concentrates on steps 1, 2, 3, 5 and 6. In the first step, the problem formulation, SRQ 4 is referenced to identify the key stakeholders and institutions and to examine how they may facilitate or hinder the development of OTEC in Aruba.

In the second step - identifying the stakeholders involved - the approach outlined by Verbong and Geels [140], where stakeholders are categorised into social actor groups (government, market and society) is applied. For the purposes of this study, the 'government' category is further subdivided into local government and international governmental bodies, and an additional social actor group category, ’Knowledge Institutions’, is introduced to address relevant academic and research entities. An overview of these revised categories is presented below.

1. Market: stakeholders operating in commercial markets. This includes but is not limited to the electricity sector in Aruba.
2. Local Government: the Government of Aruba, which consists of ministries and is further divided into departments.
3. International Governmental Bodies: governmental bodies other than the government of Aruba such as the Government of the Netherlands and the European Union.
4. Society: stakeholders in Aruba that don’t operate in the market or government but could affect the implementation of OTEC through support or resistance.
5. Knowledge Institutes: stakeholders that are active in OTEC research through experimental OTEC setups and theoretical research aiming to contribute to the current knowledge of OTEC.

For the third and fifth steps - mapping the institutional playing field and summarising the interdependence between actors through diagrams - desk research combined with insights from expert consultations was utilised to make clear how stakeholders interact within the network. This approach facilitates an understanding of the dynamics and relationships among the stakeholders.

The stakeholder network is then represented diagrammatically, categorising stakeholders into three self proposed tiers based on the strength of their ties: strong, moderate and weak. Stakeholders within the strong ties category exhibit significant interdependence and their interactions are often crucial for the successful implementation of OTEC in Aruba. Conversely, the importance of interactions decreases among stakeholders with moderate ties and is minimal among those with weak ties.

The interactions among stakeholders are categorised into several distinct types, each characterised by different forms of exchange, namely: monetary interaction, the giving of electricity, giving paid advice or knowledge, giving general (non-specialised) knowledge without being paid and enforcing policies or rules. The types of interactions are listed again below with their corresponding label and colour.

- Monetary transactions [USD]
- Transfer of electricity [kWh]
- Provision of paid advice or knowledge [Advice]
- Sharing of general knowledge without financial compensation [Information]
- Enforcement of policies or regulations [Policies (dashed)]

Each category is annotated to indicate the label and colour of the exchange arrow in the diagram to provide clarity on the type of interaction involved. A representation of the diagram’s structure is presented in Figure 4.8.

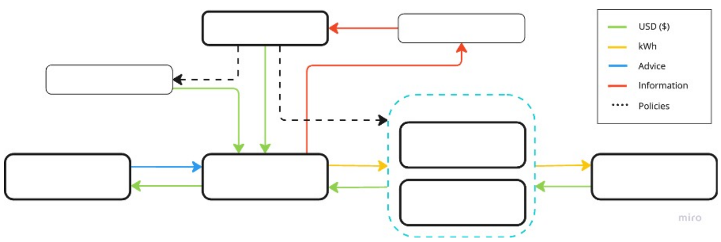


Figure 4.8: Representation of the stakeholder network diagram’s structure.

Lastly, the sixth step - determining the consequences of these findings with regards to the problem formulation - is addressed in the stakeholder analysis conclusions.

4.3.2. PESTEL Framework

To obtain a broader understanding and perspective of Aruba's social economic climate and what factors could play a role in enabling or constraining OTEC's implementation a PESTEL analysis is conducted. PESTEL is an acronym for the defined segments of the macro-environment and stands for Political, Economic, Social, Technological, Environmental and Legal [141]. This analysis method is widely used in business and management to analyse the environment they are operating in.

The framework is firstly applied to identify important factors that could enable or constrain OTEC's development in Aruba, employing desk research. Given the scarcity of academic journal literature on Aruba's current socio-economic environment, this analysis primarily relies on industry reports, thesis papers, online sources, local articles and Aruban government documents as source material.

Subsequently, the findings are examined during expert consultations with two individuals: one with expertise in Aruba's electricity sector and the other with knowledge of OTEC and Aruba. During these consultations, the framework serves as a comprehensive checklist to ensure that all relevant aspects are thoroughly discussed.

For this work the factors, as defined in Yudha et al. (2018) [142] are adopted.

Political: these factors determine the extent to which a government may influence the economy or a certain industry sector, such as the electricity sector. This could be done through for instance the stimulation of renewable industries through tax incentives. Political factors may include tax policies, fiscal policy, trade tariffs, etc., which may significantly affect the business or economic environment.

Economic: these factors directly impact the economic performance of an organisation, market, industry sector or even a country, and have resonating long-term effects. For example, an increased inflation rate would affect the way organisations modify the pricing structure of their products, influencing the purchasing power of consumers and eventually changing the level of demand and supply for that economy. Economic factors typically include inflation rate, interest rates, foreign exchange rates, economic growth patterns, etc.

Social: these factors examine the social environment of the industry sector, economy or market that impacts on other factors such as demographics, cultural trends, population analytics, etc. An example of this can be social perception of certain technologies with associated impacts and incentives which could increase or diminish acceptability from the local public.

Technological: these factors are related to the technological innovation that may affect the operations of an organisation, industry sector or market, be they favourable or unfavourable. This includes automation, R&D and the technological awareness that exists in the organisation or market. Technological factors can include for example technological readiness or advantages or disadvantages compared to other technologies in the industry sector or market.

Environmental: these factors include all those that are influenced or determined by the surrounding environment. Environmental factors are certainly critical for the energy sector. They include local climate, weather, geographical location, global changes in climate, environmental offsets, etc.

Legal: these factors take into account both policies and laws that affect the industry or organisation and then map out the strategies in light of these legislations. These include safety standards, labour laws, consumer protection laws, etc., that affect performance due to maintaining certain policies or adhering to certain directives.

4.3.3. Key Stakeholders for Implementation

To identify key stakeholders for the implementation of OTEC in Aruba, a proposed influence matrix is constructed. The analysis of these key stakeholders is subsequently integrated into the Roadmap.

The proposed influence matrix consists of two axes. The y-axis is denoted by the ability of a stakeholder to help, with a higher positive y value allocated to stakeholders with a greater ability to help. The x axis is denoted by the ability of a stakeholder to hinder OTEC's implementation, with higher positive x values allocated to stakeholder with a greater ability to hinder. A graphical representation of the matrix is provided in Figure 4.9.

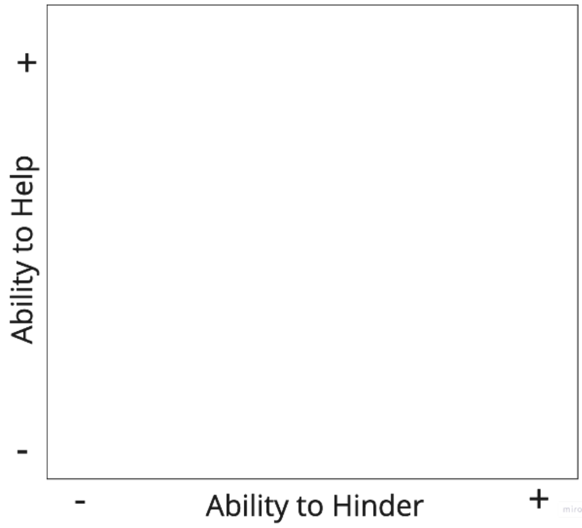


Figure 4.9: Proposed structure of influence matrix to identify key stakeholders.

To systematically categorise the stakeholders within the matrix, scores ranging from 1 to 5 are assigned to each stakeholder. One score denoting their capacity to help and one for their ability to hinder OTEC's implementation. These scores are subsequently documented in a table, which is included in Appendix E. Finally, the data are visually represented on an influence matrix to illustrate the relative impact of each stakeholder.

4.3.4. Roadmap

Implementation of RETs, such as OTEC, are highly complex and have an inherent high level of uncertainty, with long time horizons. To help visualise a potential approach to OTEC's implementation in Aruba, a roadmap is applied. As stated by Blackwell et al., 2008 [143] the underlying concepts for roadmaps are very flexible and have been adapted to suit many different goals such as supporting innovation, strategy and policy development and deployment. This adaptability has led to their widespread adoption, resulting in a diverse array of methodological approaches.

Based on roadmaps described in Phaal et al., 2004 [144] a roadmap is developed, with the goal to provide a high level view of the necessary steps that could be taken to implement OTEC in Aruba in the future. To develop the roadmap the following steps are undertaken:

1. Formulate the current state of OTEC in Aruba and define the objective.
2. Develop a timeline for the global technological development necessary for OTEC in Aruba.
3. Develop a roadmap for implementing OTEC in Aruba.

The approach employed per step is described in more detail below.

<u>Formulate the current state of OTEC in Aruba and define the objective</u>

To effectively structure the goal of the roadmap, a clearly defined objective is essential. To ensure that this objective is realistic, an evaluation of the current state of OTEC in Aruba is necessary. This evaluation draws upon findings from both the power system modelling and the stakeholder analysis chapters. These findings are reviewed to assess the present status of OTEC in Aruba and to establish a realistic timeline for its implementation.

<u>Develop a timeline for the global technological development necessary for OTEC in Aruba</u>

Given that OTEC is still in a pre-commercial phase, a brief analysis of the steps necessary to advance OTEC to a commercial phase on a global scale is described. Drawing on insights from previous sections and desk research of other offshore projects, this analysis delineates required steps and provides estimates for the duration of each step. These durations are subsequently illustrated in a timeline, incorporating margins to account for the uncertainties associated with these time frames.

Develop a roadmap for implementing OTEC in Aruba

For the development of the roadmap, this work builds on the foundational work of Phaal et al., 2004 [144]. As detailed by Phaal et al., roadmapping is a strategy that has been widely adopted across various industries and can be adapted into various forms. In this work, one of the most common approaches proposed by the European Industrial Research Management Association [145], as depicted in Figure 4.10, is employed. This generic roadmap is a time-based chart that integrates several layers, typically capturing both commercial and technological dimensions. It facilitates the exploration of the evolution of markets, products and technologies, including their interconnections and potential discontinuities. Moreover, the roadmapping technique effectively synthesises key concepts from technology strategy and transition literature, by the use of its layered structure in conjunction with the dimension of time.

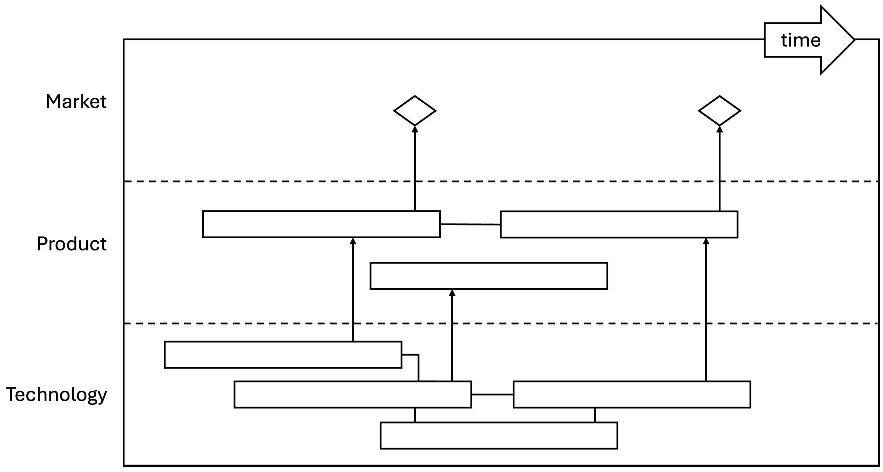


Figure 4.10: Schematic technology roadmap, aligning technology with business strategy [145].

The design is adjusted for the purpose of this work to include three phases in time; the monitoring stage, decide & structure stage and the development stage. The adjusted format is presented in Figure 4.11.

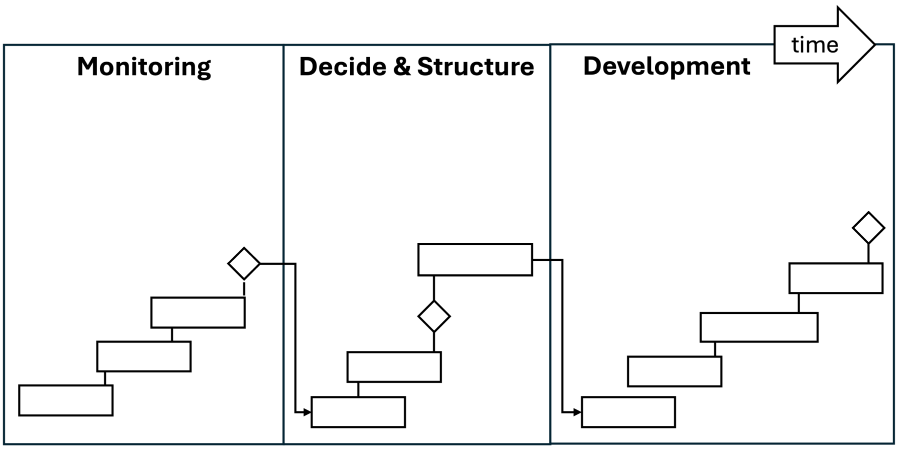


Figure 4.11: Adjusted schematic technology roadmap for OTEC's implementation in Aruba.

5

Techno-Economic Analysis

The chapter begins with an assessment of RETs applicable to Aruba, presented in Section 5.1. Following this, Section 5.2 discusses the results of the technical analysis of viable RETs in Aruba. Finally, Section 5.3 provides a comparative economic analysis of the identified RETs.

5.1. Assessment of RETs applicable in Aruba

To develop a comprehensive understanding of the potential RETs that could be integrated into Aruba's future power generation mix, literature research is conducted into the current state of the art of RETs [146, 147, 148, 149]. The resulting RETs that are explored for their applicability in Aruba include: (1) OTEC, (2) utility-scale land-based solar PV, (3) floating solar PV, (4) onshore wind turbines, (5) offshore wind turbines, (6) nuclear energy, (7) biomass energy, (8) geothermal energy, (9) hydroelectric power, (10) tidal energy, (11) wave energy and (12) salinity gradient energy.

Furthermore, storage technologies are investigated due to their critical role as buffers to manage and balance the variable power generation from RET resources and fluctuating load demands [146]. It is noted that large-scale energy storage solutions remain significantly expensive, with the exception of geographically dependent *Pumped Storage Hydropower* (PSH) systems. In this analysis, three storage technologies are examined: (1) BESS, (2) PSH and (3) Hydrogen [96].

5.1.1. Generation Technologies

An analysis of the resource requirements for various technologies indicates that Aruba lacks access to the necessary resources to operate several of the assessed energy technologies. These include biomass energy, geothermal energy, hydroelectric power, tidal energy, wave energy and salinity gradient energy.

Biomass

Due to Aruba's dense population, arid terrain and dry climate, there is minimal arable land available for cultivating the necessary feedstocks for biomass production (e.g. biodiesel, ethanol) [150]. Consequently, substantial quantities of biofuels would need to be imported, exposing Aruba to similar risks of price volatility and supply interruptions as those associated with fossil fuel imports. While there is potential for cultivating aquatic biomass such as algae for biofuel production [151], no comprehensive studies have been identified that provide clear estimates of its feasibility. Therefore, these resources are not specifically addressed in this analysis.

Hydro power and Geothermal energy

Aruba's arid and flat geography does not facilitate the implementation of hydro electrical power plants [150]. Furthermore, Aruba is located on the southern side of the Caribbean tectonic plates. This region lacks volcanic activity, which implies a lack of high temperature geothermal potential. The Caribbean does have a geothermal active arc roughly stretching north to south from Saba and St. Kitts to St.

Vincent and Grenada [152] as depicted in Figure 5.1. However, Aruba is not located close enough to take advantage of this geothermal activity.

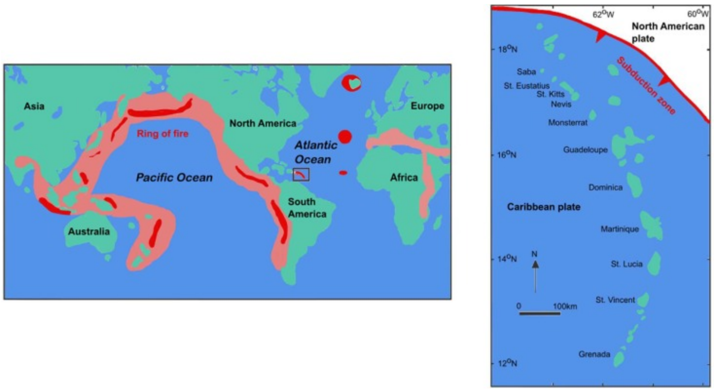
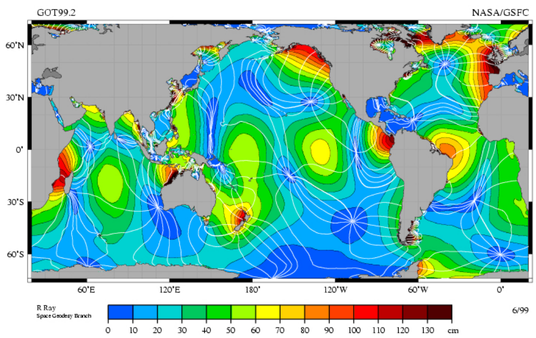


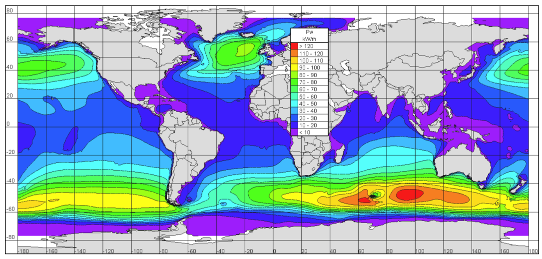
Figure 5.1: Global geothermal activity map with snapshot of Eastern Caribbean States. [153].

Salinity gradient, Tidal energy and Wave energy

Assessing the potential for salinity gradient energy in Aruba reveals minimal to no prospects due to the absence of significant freshwater streams, rendering the exploitation of salinity gradients as a renewable resource negligible [154]. Regarding tidal energy, the Caribbean, including Aruba, experiences low tidal ranges, typically less than one meter, and lacks the steep geographical features necessary for effective tidal power generation. Consequently, Aruba does not possess substantial tidal energy potential, as illustrated in Figure 5.2a [155, 69]. Wave energy potential is slightly more promising, yet remains modest, with an estimated potential of approximately 5 kW/m [156] (Figure 5.2). A higher spatial resolution analysis of the Caribbean Sea's wave energy potential reveals a hot-spot with wave power densities of 18 kW/m off the north coast of Colombia. However, the wave energy potential surrounding Aruba is still approximately 5 kW/m [157] (Figure 5.3). This limited potential is primarily attributed to the moderate wave climate characteristic of the south eastern Caribbean Sea, which seldom experiences large ocean swells or high-energy waves [158]. Furthermore, the presence of coral reefs in the region serves to attenuate wave energy, further diminishing its viability [69].



(a) Global Tidal Potential [159]



(b) Global Wave Energy Potential [156]

Figure 5.2: Global Tidal and Wave Energy Potentials.

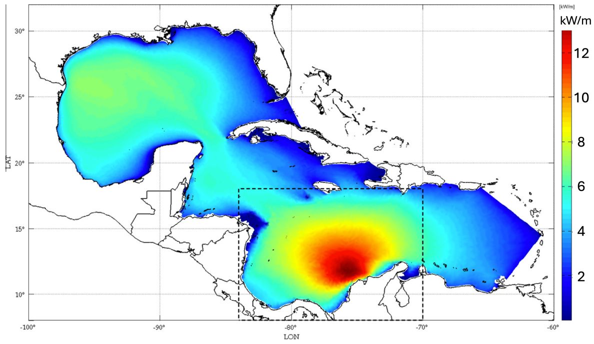


Figure 5.3: Caribbean Wave Potential [157].

Nuclear

Although nuclear energy is technically feasible in the Carribean, as demonstrated by the presence of a research reactor at the University of West Indies in Jamaica [160], it has been excluded from this analysis due to Aruba's relatively small size. The scale of conventional nuclear power plants would be excessive relative to the island's size and energy requirements. While smaller, modular nuclear reactors present an emerging alternative, they still demand significant investment and technological infrastructure [161]. Furthermore, there are environmental concerns associated with nuclear waste management [162]. On a small, tourism-dependent island like Aruba, environmental incidents related to nuclear energy could have harmful effects on both the local ecosystem and the economy.

Applicable Technologies

Analysing the remaining generation technologies it is assessed that the following generation technologies are applicable on Aruba: (1) utility-scale land-based solar PV, (2) floating solar PV, (3) onshore wind turbines, (4) offshore wind turbines and (5) OTEC. These will be investigated further in this work with the technical potential of these RETs being described in Section 5.2.

5.1.2. Storage Technologies

An analysis of the resource requirements for storage technologies reveals that Aruba lacks the geographic conditions necessary for PSH. Additionally, it is determined that hydrogen storage could be a viable option for Aruba, while BESS has already demonstrated its viability, as evidenced by its current implementation on the island.

Pumped Storage Hydropower

Due to Aruba's arid and flat geography depicted in Figure 5.4 Aruba is not a viable location for PSH. The island has a limited amount of elevation on the south east reaching no more than about 130m and is enclosed in a nature reserve [163].

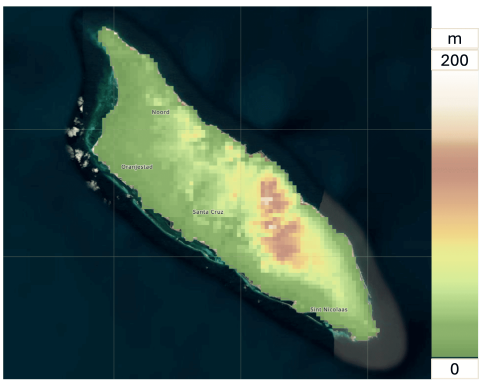


Figure 5.4: Orography Aruba (0-200m) [98].

Hydrogen Storage and BESS

Hydrogen energy storage is an umbrella term encompassing a wide range of technologies that would convert electricity generated on the island into a form of hydrogen, which can later be reconverted to electricity when needed. Principal methods of hydrogen storage include compressed hydrogen, liquefied hydrogen, cryocompressed hydrogen, physically adsorbed hydrogen, metal hydrides, complex hydrides and liquid organic hydrogen carriers [164]. In addition to its role in energy storage, hydrogen has applications in various non-power sector uses, such as transportation, heating and cooling [165, 166]. This work primarily concentrates on Aruba's power system; therefore, hydrogen is excluded from the model due to its diverse range of applications. However, hydrogen could be integrated into the model in the future when it is expanded to a total energy system perspective. BESS technology is currently operational in Aruba [19] and has been implemented on a larger scale in power grids in countries such as the United States, China and Australia [95, 167]. In this study, BESS technology is integrated into the model.

5.2. Technical Analysis

5.2.1. Ocean Thermal Energy Conversion

The conditions in Aruba are found to be favourable for OTEC. The sea off the coast of Aruba has high ocean thermal energy potential as can be seen in Figure 5.5. This high potential is defined as the recoverable potential available from the difference in temperature found between the warm ocean's surface and its colder deeper layers [168].

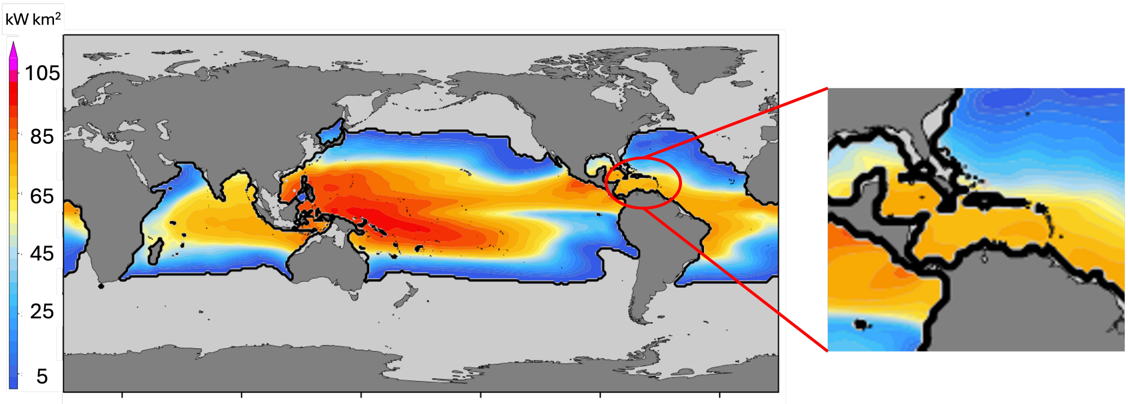


Figure 5.5: Geographic distribution of global time-mean (1992–2021) OTEC power potential density zoomed in on Aruba [168].

OTEC installations would need to be located within Aruba's EEZ, which is legally defined as 'an area of the ocean, extending beyond a nation's territorial sea, where a coastal nation exercises jurisdiction over both living and nonliving resources' [169]. The spatial extent of Aruba's EEZ is illustrated in Figure 5.6. While OTEC facilities are legally allowed to be positioned anywhere within this zone, they would most likely be situated as close to the coast as possible, minimising transmission cable costs and helping to mitigate potential conflicts with shipping routes. This analysis is conducted within the EEZ.

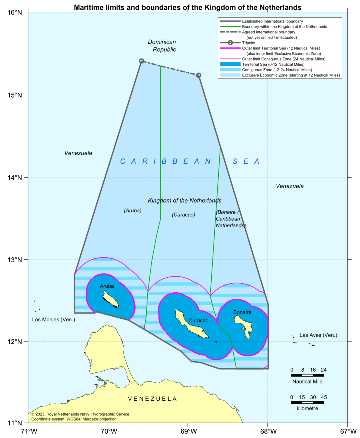


Figure 5.6: Aruba's Exclusive Economic Zone [170].

Geographic analysis of the ocean off the coast of Aruba indicates that the ocean's surface temperature profile is well suited for OTEC implementation. Positioned near the equator, between 20◦N and 20◦S, Aruba experiences an average sea surface temperature of 28.3°C [28] as presented in Figure 5.7.

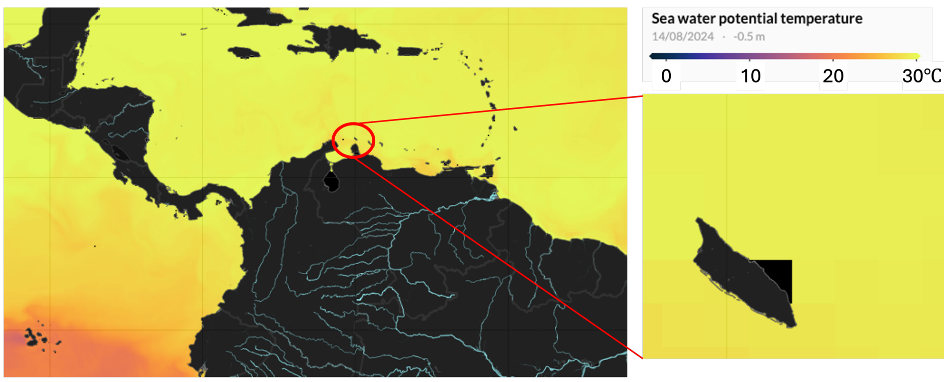


Figure 5.7: Sea surface temperature of the Caribbean Sea and Aruba [28].

Moreover, the surface temperature remains consistently above 25°C, with recorded fluctuations ranging from 25.9°C to 30.8°C in 2023. The average DSW temperature was found to be 4.9°C, with fluctuations between 4.1°C and 5.5°C during the same period. The temperature difference between the surface and DSW was consistently above 21°C, reaching a maximum of 25.5°C. Figure 5.8 illustrates the sea surface temperature and the temperature at a depth of 1000 meters throughout the year 2023.

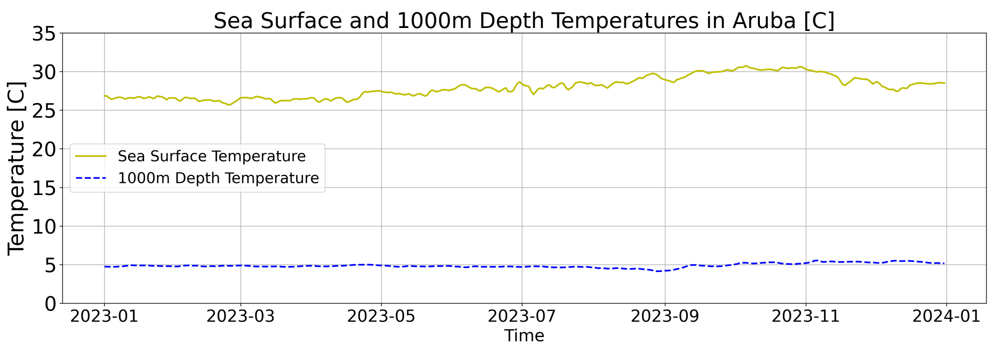


Figure 5.8: Sea surface and 1000m depth temperature off the coast of Aruba throughout 2023 [28].

The consistent temperature difference exceeding 21°C suggests that Aruba is a suitable location for OTEC. This is further supported by the results obtained using the pyOTEC model. As shown in Figure 5.9, the capacity factor profile derived from pyOTEC indicates stable power production throughout the year

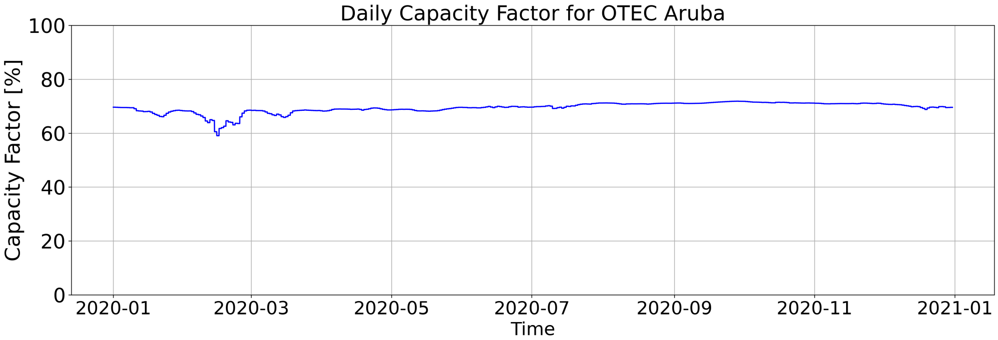
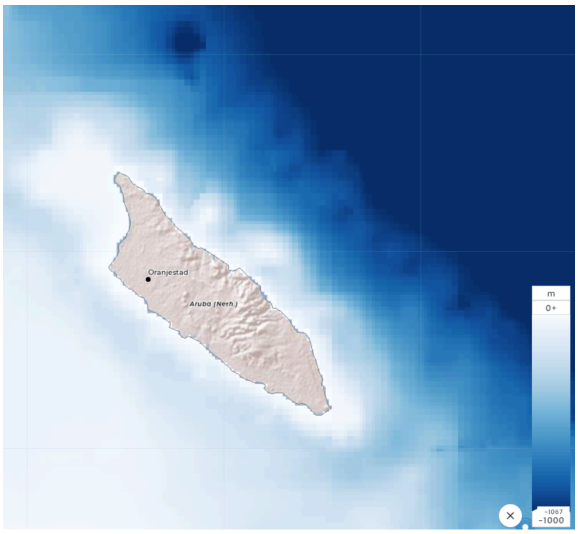


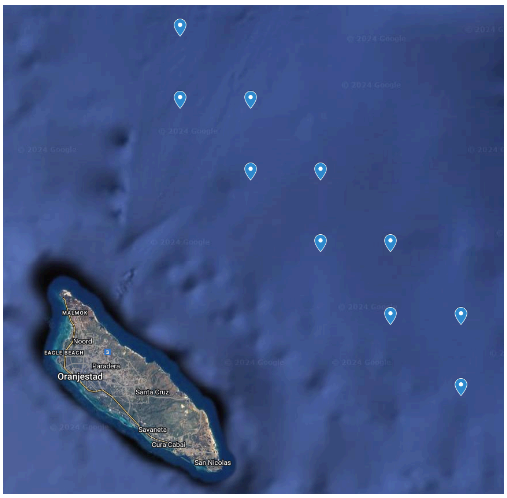
Figure 5.9: Hourly capacity factor profile for Aruba [112].

An analysis of Aruba's bathymetry, as depicted in Figure 5.10a, reveals that deep waters is accessible primarily on the eastern side of the island. Here, water depths of approximately 600 meters are located within 7 km from the southeast coast, and greater depths reaching 1000 meters are found within 10-15 km of the eastern coast.

Using pyOTEC, several potential sites for OTEC installations have been identified, as illustrated in Figure 5.10b. These locations were selected based on their minimal cost estimates.



(a) Bathymetry of Aruba's coast for OTEC (0-1000m) [171]



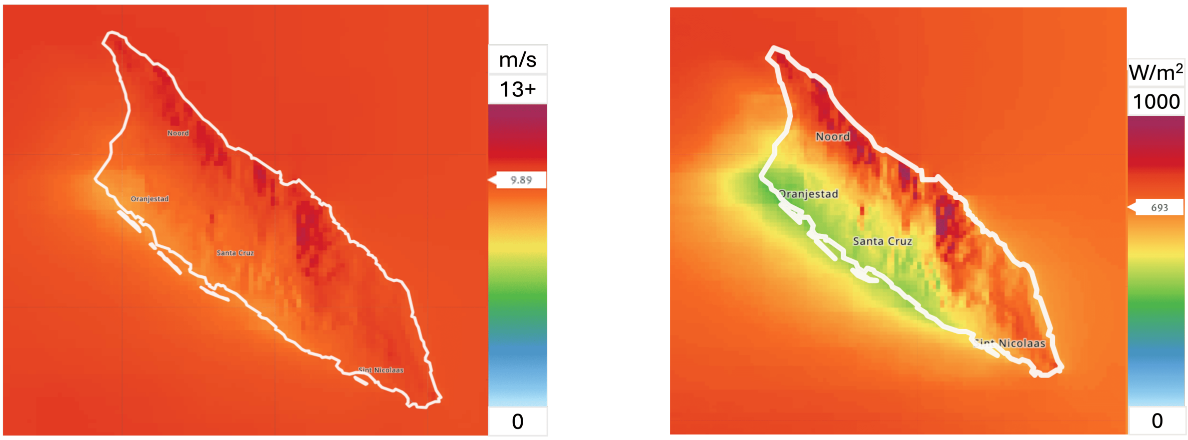
(b) Technically viable locations for OTEC installations, determined by pyOTEC analysis (visualised using Google maps).

Figure 5.10: Bathymetry and viable OTEC locations in Aruba.

5.2.2. Wind Energy

Both onshore and offshore wind systems are evaluated for potential deployment in Aruba. Initially, an overview of the general wind resources available in Aruba is presented. Subsequently, analyses of both onshore turbines and offshore turbines are provided, exploring their applicability and potential capacity in Aruba.

An analysis of Aruba's wind resources reveals that both mean wind speeds and power density are high on and around the island [98]. Colour-coded maps displaying the wind energy potential are provided in Figures 5.11a and 5.11b. Onshore, mean wind speeds fluctuate between 8.5 and 11 m/s, whereas offshore they remain relatively stable at approximately 10 m/s. Additionally, onshore mean power density exhibits significant variation, ranging from 400 W/m^2 along the northwestern coast to 1000 W/m^2 in the mountainous eastern terrain. Offshore, the mean power density is consistently around 700 W/m^2.



(a) Mean wind speeds Aruba (0-13 m/s).

(b) Mean wind power density Aruba (0-1000 W/m^2.

Figure 5.11: Mean wind speed and power density Aruba [98].

Onshore Wind Turbines

Aruba's land area is approximately 180 km^2, of which 34 km^2 is designated as Arikok National Park or other protected areas [163]. Further analysis, using area calculations, estimates that approximately 100 km^2 of Aruba's territory is currently urbanised or developed, as illustrated in Figure 5.12. After accounting for protected and inhabited areas, about 45 km^2 of land remains available. In this work 20% is assumed to be available for onshore power production i.e. 9km^2.

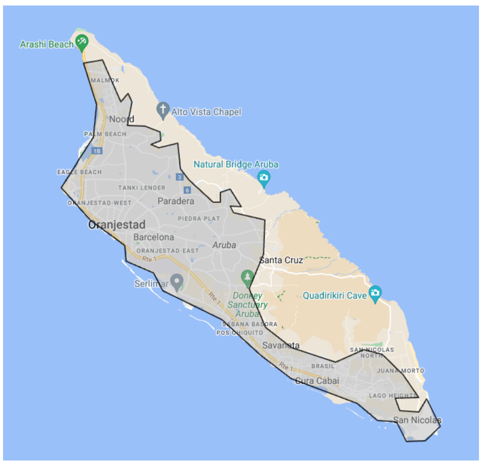


Figure 5.12: Estimated inhabited area in Aruba [108].

To assess the maximum potential capacity for onshore wind given Aruba's limited land size, the installed power densities reported by Enevoldsen et al. (2022) [172] for Europe, at 19.8 MW/km^2, are applied. Half of the available onshore land is taken for wind i.e. 4.5km^2. Multiplying the density by the available land yields an estimated maximum capacity of 89 MW for onshore wind.

Employing the renewables.ninja platform to analyse data spanning from 1980 to 2023, the year 2013 was identified as providing a representative average for both wind and solar resource availability. Consequently, 2013 has been selected for detailed analysis. The hourly capacity factors derived from this analysis are depicted in Figure 5.13.

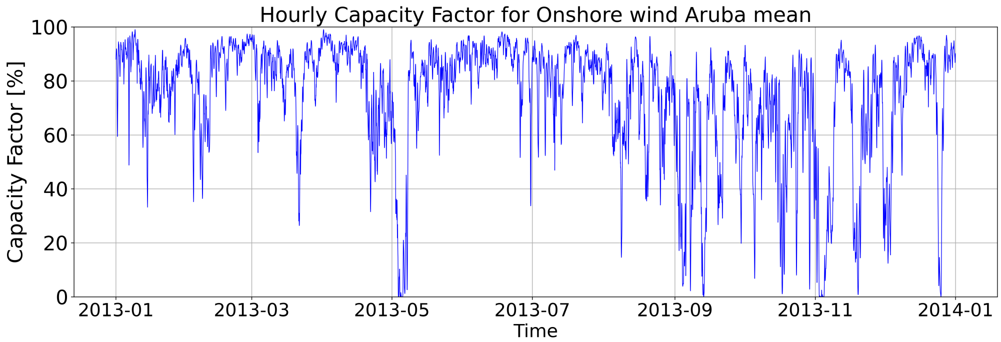


Figure 5.13: Hourly capacity factors for onshore wind in Aruba[112].

Observing the capacity factors for onshore wind on Aruba, it is noted that the average capacity factor throughout the year is high at about 74%, this is in line with expectations as Aruba shows good wind resources (see Figure 5.11b). However, the availability of wind resources does fluctuate quite heavily. Notably, there are two distinct periods where capacity factors dip sharply, the first occurring in May and a more pronounced reduction between September and November. These variations are highlighted in Figure 5.14 with the dips denoted by red circles.

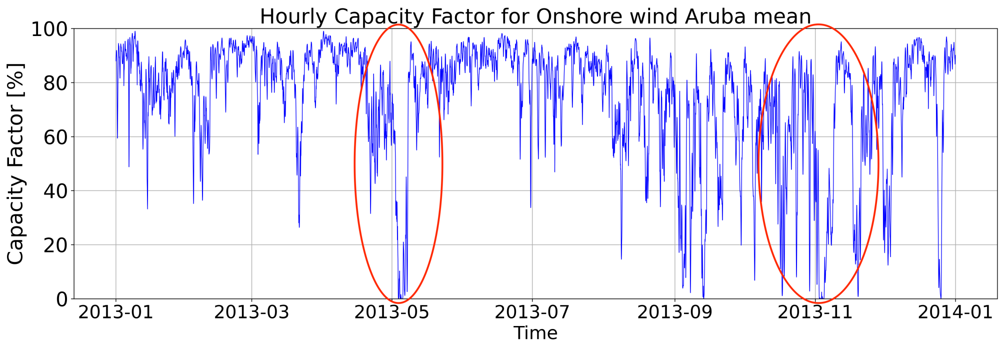


Figure 5.14: Hourly capacity factors for onshore wind in Aruba with prominent dips highlighted.

To assess the consistency of the observed patterns across multiple years, all available data from Renewables.ninja for each year are analysed. The analysis reveals that while dips in capacity factors frequently occur in the first half of the year, the most consistent and pronounced declines are observed around November. These November dips are identified as systematic, as evidenced by the average capacity factors of the period 1980-2023, presented in Figure 5.15. This alludes to a so called "dunkelflaute" or extended periods of unfavourable weather conditions leading to the decrease in renewable energy resources that occur systematically [84].

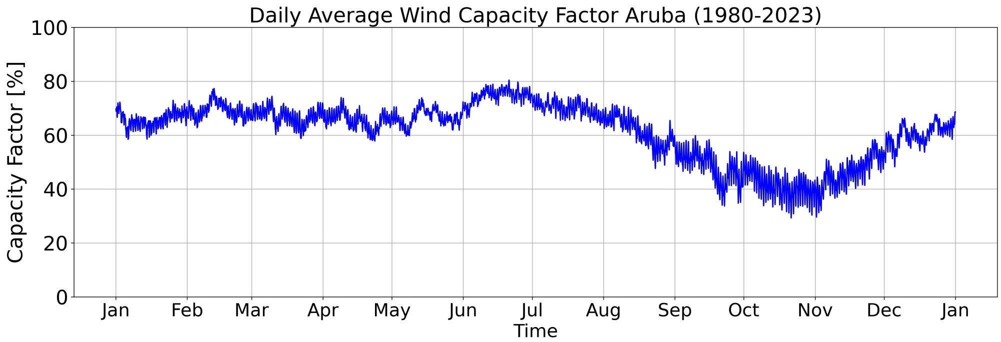


Figure 5.15: Onshore wind capacity factors averaged from 1980 to 2023 [112].

Offshore Wind Turbines

Next to onshore, offshore wind has shown high potential in various cases. With more consistent wind speeds found offshore the expected generated electricity is typically higher [92]. In this work fixed support offshore wind turbines are considered.

In this analysis, the maximum depth for the installation of fixed-support offshore wind turbines is set at 60 meters. This limitation is due to the fact that, in waters deeper than 60 meters, fixed-support structures become commercially non-viable due to significantly increased installation costs [111]. An examination of the bathymetry around Aruba reveals limited areas that meet this depth criterion, as illustrated in Figure 5.16.

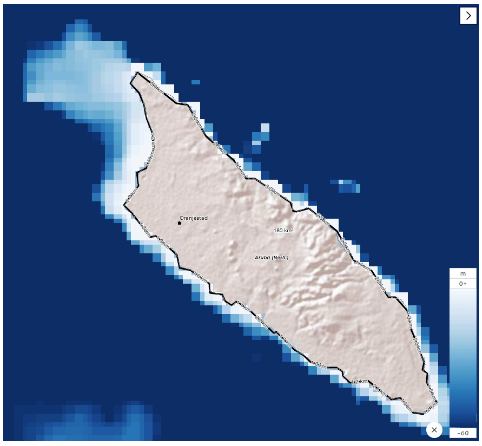


Figure 5.16: Bathymetry of Aruba's coast for offshore wind turbines (0-60m) [171].

The area off Aruba's northwest coastline is identified as the most technically feasible location for offshore wind turbines. However, this coastline is primarily occupied by hotels, serving as one of Aruba's most frequented tourist destinations. Consequently, the practicality of deploying offshore wind turbines in this region is questionable. There is a potential conflict of interest with the tourism industry, as the presence of wind turbines could adversely affect the ocean views that are influential to the area's appeal.

Despite the potential conflicts with tourism interests, this region is included in the assessment of the technical potential for offshore wind energy in Aruba. Utilising an area calculator, the available area is determined to be approximately 30 km^2. Given the average of power densities reported in literature at 6 MW/km^2 [173, 174, 175], the total feasible capacity for offshore wind in Aruba is calculated to be 180 MW.

To assess the consistency of Aruba's offshore wind resources, capacity factors derived from Renewables.ninja are analysed. The analysis focuses on the sea off the northwestern coast, identified as the most technically viable location for wind turbines. The hourly capacity factors from this location are depicted in Figure 5.17.

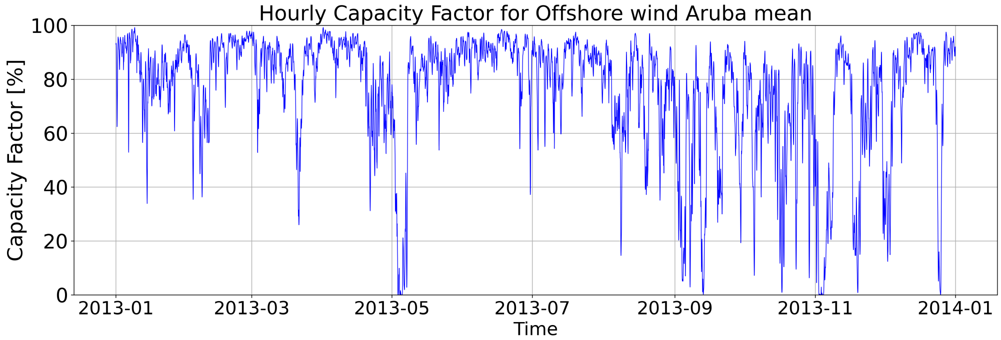


Figure 5.17: Hourly capacity factors for offshore wind in Aruba [112].

Adjusting the location to onshore, indicates only a slight variation in capacity factors, suggesting minimal impact by the turbine's placement relative to the shore. This observation might stem from Aruba's relatively compact size and flat geography, which results in relatively uniform wind speeds across both onshore and offshore locations, as illustrated in Figure 5.11a.

5.2.3. Solar Energy

Both utility-scale land-based and floating PV systems are evaluated for implementation in Aruba. Initially, an overview of the general solar resources available in Aruba is presented. Subsequently, analyses of both utility-scale land-based and floating PV systems are provided, exploring their specific applicability and potential capacity in Aruba.

Aruba boasts one of the highest specific photovoltaic power output indices in the Caribbean (Figure 5.18, averaging approximately 1821 kWh/kWp per year [100], which corresponds to about 5.7 sun hours per day [70]. This calculation assumes an optimal solar panel tilt of 13-14 degrees.

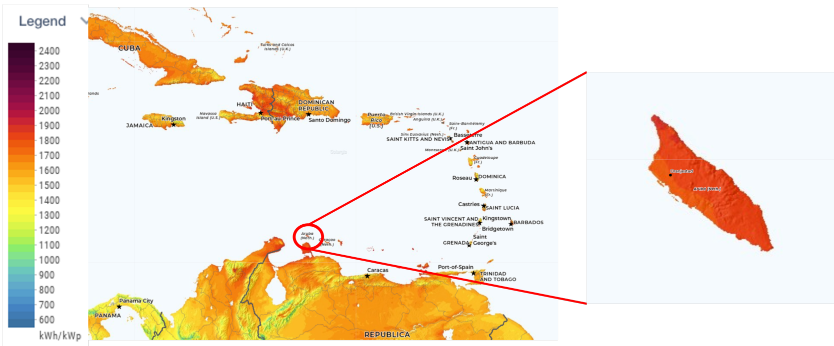


Figure 5.18: Specific PV Power output in Aruba [kWh/kWp/year][100].

Offshore solar resources northeast of Aruba are slightly higher compared to onshore, at 1850 kWh/kWp per year, while those off the western coast are lower, at 1750 kWh/kWp. Despite these variations, the differences are minimal, allowing the assumption of equivalent solar resources for land-based and floating installations.

Utility Scale Land Based Solar PV

Progress towards utility-scale solar PV implementation in Aruba is demonstrated by the installation of a 3.5 MWp solar power park at Beatrix Airport [176] and the construction of the 6 MWp Sun Rise solar park [177]. Utility-scale PV is defined in this context as large-scale installations (greater than 1 MW) specifically engineered to deliver electricity to the grid on a significant scale [178].

(a) Solar panel installation at Beatrix Airport Aruba [179]. **(b)** Sun Rise Solar Park Aruba [180].

Figure 5.19: Solar park installations in Aruba.

Empirical analysis conducted by Bolinger et al. (2022)[118] established the power density [MWp/km^2] of fixed-tilt utility-scale PV systems at 86 MWp/km^2. In this work, fixed-tilt panels are selected due to their higher energy density [MWh/year/km^2] compared to tracking panels [118]. As outlined in the previous Section 5.2.2, the land available for land based utility scale solar PV is assumed to be 4.5km^2. This area allows for a maximum potential capacity of 389 MWp for utility-scale solar PV installations in Aruba.

Using the renewables.ninja platform to analyse data spanning from 1980 to 2023, the year 2013 was identified as providing a representative average for both wind and solar resource availability. Consequently, 2013 has been selected for detailed analysis. The daily capacity factors derived from this analysis are depicted in Figure 5.20.

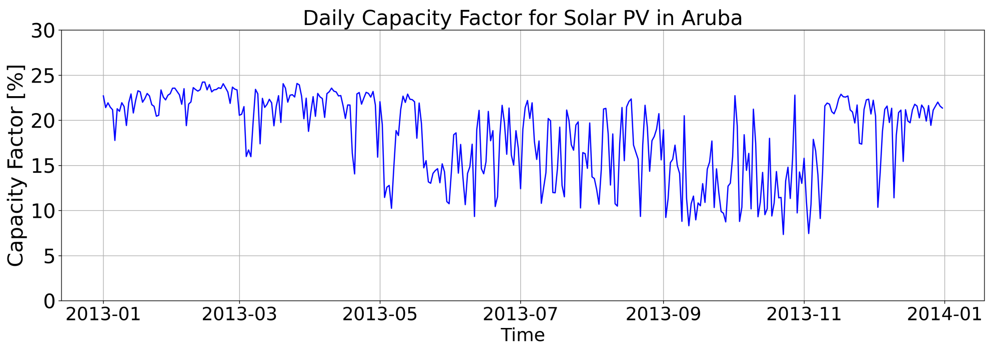
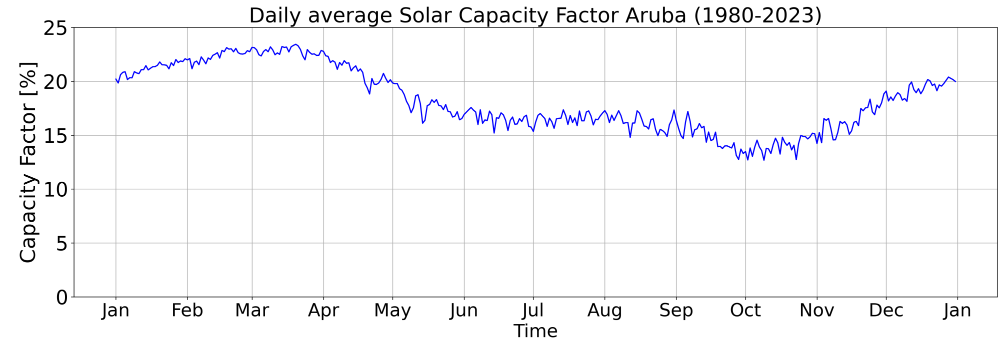
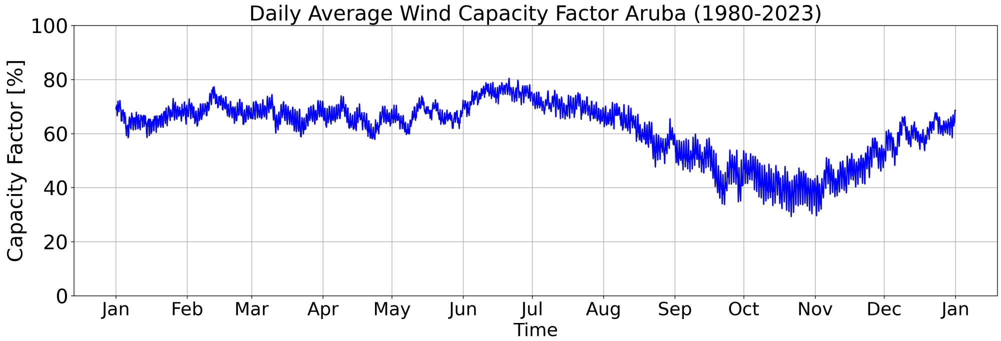


Figure 5.20: Daily capacity factor from utility scale land based solar in Aruba [112].

Analysing the capacity factors for Aruba, it reveals a high average capacity factor of approximately 22%, from January to April. There is a notable decrease in capacity factors during the months of June to November, indicating a decrease in solar irradiation during this time. This seasonal variation has been consistently observed over the period from 1980 to 2023, as detailed in Figure 5.21a. This alludes to a so called ”dunkelflaute”, extended periods of unfavourable weather conditions leading to the decrease in renewable energy resources [84].



(a) Daily average solar capacity factor in Aruba based on data from 1980-2023 [112].



(b) Daily average wind capacity factor in Aruba based on data from 1980-2023 [112].

Figure 5.21: Daily average solar and wind capacity factors (1980-2023).

Analysis of solar and wind resource data during the period 1980 to 2023 reveals a notable decrease in both resources from September to November, as shown in Figures 5.21. This seasonal reduction in available resources, or dunkelflaute, suggests that establishing a fully renewable energy system based solely on solar and wind power in Aruba would necessitate substantial BESS capacity or heavily oversizing the system. The purpose of this extensive storage would be to compensate for the dunkelflaute during these months, ensuring consistent supply and meeting ongoing demand.

Floating Solar PV

Floating PV (FPV) technology has seen significant development since 2016 [181], with an increasing body of research emerging in recent years [182, 183, 184, 185, 119]. As of March 2024, there are over 350 operational FPV projects globally [186], predominantly situated on lakes or artificial water bodies such as reservoirs, which offer calmer environmental conditions. The deployment of FPV to offshore environments is progressing, exemplified by the successful deployment of Oceans of Energy's North Sea 1 and 2 projects in the North Sea [187]. However, offshore FPV, necessary for Aruba due to the absence of suitable inland water bodies, remains in the developmental phase and requires further research for commercial scale implementation. Despite these challenges, the potential for FPV in Aruba is considerable and is included in this analysis to assess its role in the future electricity generation mix of the island.

An analysis of the bathymetry within Aruba's EEZ and the solar potential off its coast indicates that the southern tip of the island (Figure 5.22) may represent the most suitable location for FPV installations. This region features relatively shallow waters, approximately 60 meters deep [98], and benefits from high specific photovoltaic power output of 1827 kWh/kWp [100], while being in close proximity to the island. However, this area has been recently designated as protected wetlands under the Ramsar Convention [107], which could impose restrictions on development. As an alternative, Area 2 (Figure 5.22) located further off the west coast, also demonstrates comparable solar resources and shallow waters, making it a promising site for FPV deployment, further off the coast.

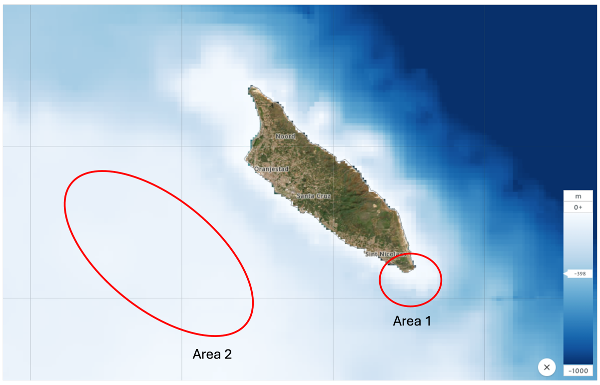


Figure 5.22: Bathymetry of Aruba's coast for Floating PV (0-1000m) including area 1 & 2.

The total area of Aruba's EEZ is determined to be 25,488 km^2 [170]. For the purposes of this analysis, it is assumed that the maximum available capacity of FPV installations will not be a limiting factor, given the extensive potential available. Covering just 1 percent of Aruba's EEZ with FPV could generate sufficient electricity to exceed Aruba's annual electricity demand several times over. However, the technological maturity, associated costs and challenges related to the storage of large quantities of electricity currently are expected to pose barriers to the deployment of this technology.

The daily capacity factor for FPV off the west coast of Aruba is provided in Figure 5.23. The resource availability is found to be comparable on and offshore shore. Floating solar systems benefit from increased efficiency due to the cooling effect of water [119], however higher losses are expected for the FPV due to higher levels of soiling as a result of to bird droppings and salt formation, spectral mismatching and transmission losses to land [120, 121].

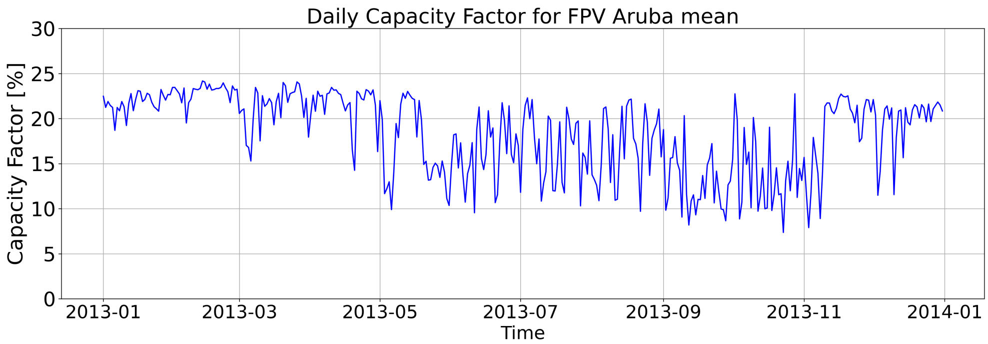


Figure 5.23: Daily capacity factor for FPV off the west coast of Aruba[112].

5.2.4. Battery Energy System Storage

The analysis assesses the required size of a BESS in Aruba for a system powered by either wind or solar resources. The integration of BESS with multiple RETs is further examined in Chapter 6. This analysis provides preliminary insights into the required battery storage capacity, based on the assumption that there is no interconnection between the technologies.

Lithium-ion batteries are the most widely used technology in global BESS deployments, accounting for 89% of electrochemical storage systems. As such, lithium-ion batteries have been selected for this analysis. An overview of observed BESS development is provided in Appendix B.

For the power system reliant on wind resources the required BESS storage capacity is estimated to be approximately 204 GWh. The SoC curve is presented in Figure 5.24.

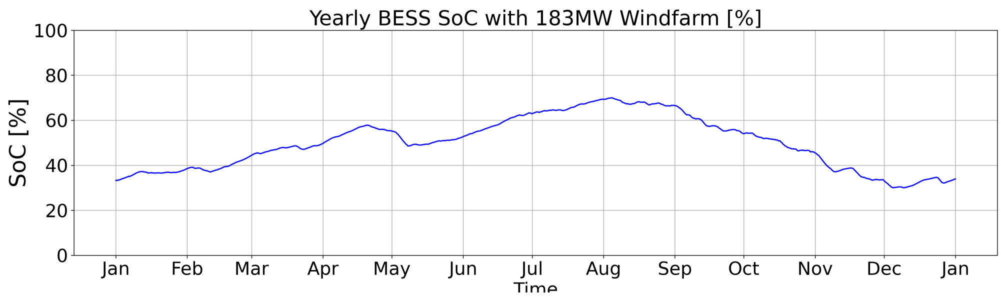


Figure 5.24: Battery storage curve for a 183 MW wind farm with battery storage on Aruba.

For a power system dependent on solar resources, the required BESS storage capacity is estimated to be approximately 213 GWh. The SoC profile for this system is illustrated in Figure 5.25. The battery storage curves used to determine the solar and wind farm SoC curves can be found in Appendix C.

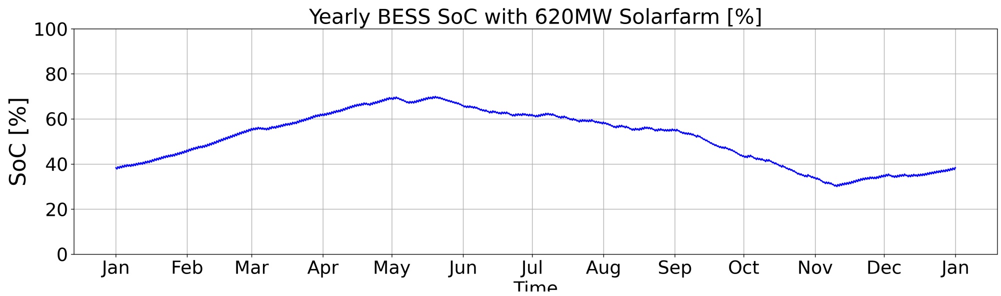


Figure 5.25: Battery storage curve for a 620 MW solar farm with battery storage on Aruba.

The estimated BESS storage capacities required for wind- and solar-driven power systems are 204 GWh and 213 GWh, respectively, which are exceptionally large compared to current BESS facilities. The largest operational BESS facility has a storage capacity of approximately 3 GWh [188]. It is noted that the SoC curve aligns with the expected impacts of dunkelflaute, as noted in subsection 5.2.3, with the SoC of the BESS significantly dropping for both systems between September and November. Furthermore, to meet peak demand during periods without solar or wind generation, the batteries would require a power capacity of 155 MW [19]. While BESS facilities with power capacities exceeding 800 MW are already in operation [188], most existing systems are designed for 4-hour storage, with a few extending up to 10 hours [97]. Operating a BESS with year-long storage capacity is currently unprecedented. For storage durations beyond several days, self-discharge rates and parasitic losses are expected to increase significantly, resulting in substantial energy losses [134]. This would likely require either increased energy generation to compensate for these losses or the deployment of even larger BESS capacities.

These estimates pertain to systems powered exclusively by wind or solar farms, sized to exactly match Aruba's total annual electricity demand. Increasing the capacity of these farms or integrating both wind and solar energy into the system would likely reduce the required storage capacity [GWh] of the BESS. This is further explored through power system modelling in Section 6.

This analysis underscores a critical challenge for SIDS without access to renewable storage options such as PSH when transitioning to fully renewable energy systems reliant on intermittent sources. Due to dunkelflaute events, the need for storage is expected to increase significantly and non-linearly as the share of intermittent renewables in the energy mix grows. This will require either substantially oversizing the capacity of supply technologies or the integration of a baseload technology like OTEC. While a BESS is likely viable for short-term storage in Aruba, they are not expected to be cost-effective for long-term, year-round storage in a fully renewable energy system.

5.3. Economic Analysis

To explore the economic viability of potential renewable energy technologies in Aruba, industry reports and scientific papers are consulted to gather Capex and Opex data for each technology. This data is subsequently used to calculate the LCOE for each technology, initially excluding and then including the associated costs of necessary battery storage.

5.3.1. Technology Costs

The ascertained global Capex and Opex costs of the reviewed technologies, covering the period from 2020 to 2025, are depicted in box and whisker plots shown in Figure 5.26.

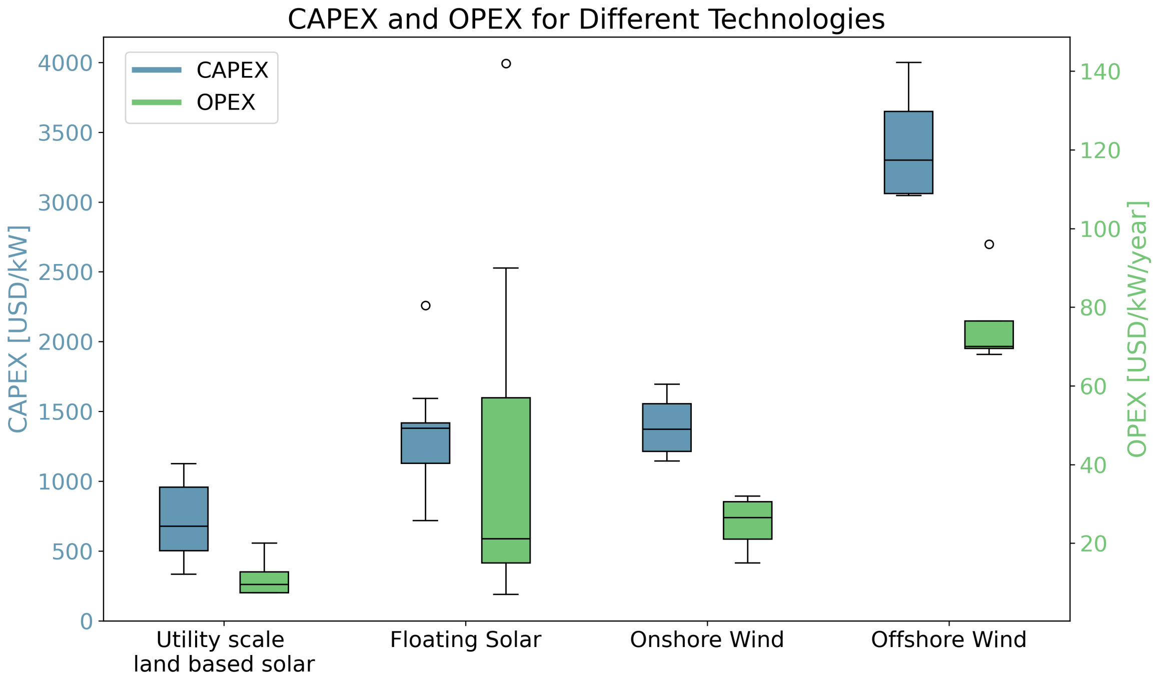


Figure 5.26: Box and Whisker plot of RET Capex and Opex.

Analysis reveals significant variability in the costs associated with the RETs examined. For instance, the Capex for offshore wind projects in Japan and South Korea are approximately twice the global weighted average at about 6,700 USD/kW, likely due to more challenging marine conditions and higher labour and material costs [189]. Furthermore, the Capex for utility-scale land-based solar exhibits large variation, ranging from as low as 333 USD/kW to as high as 1,225 USD/kW. Notably, Capex estimates for floating PV systems are relatively consistent, despite the technology being relatively new; however, Opex costs exhibit significant variability. This cost disparity is likely attributed to the more challenging environmental operating conditions, which result in increased expenses for maintaining floating systems compared to land-based installations [119].

5.3.2. LCOE per Technology

To compare the economic viability of the technologies an LCOE calculation is performed to estimate the current cost of electricity per technology. To calculate the LCOE, data presented in Figure 5.26 are utilised. Considering Aruba's geographical isolation and the scarcity of local expertise, the cost estimates employed are adjusted above the mean to account for these factors. The resultant LCOE values, excluding battery storage costs, are depicted in Figure 5.27.

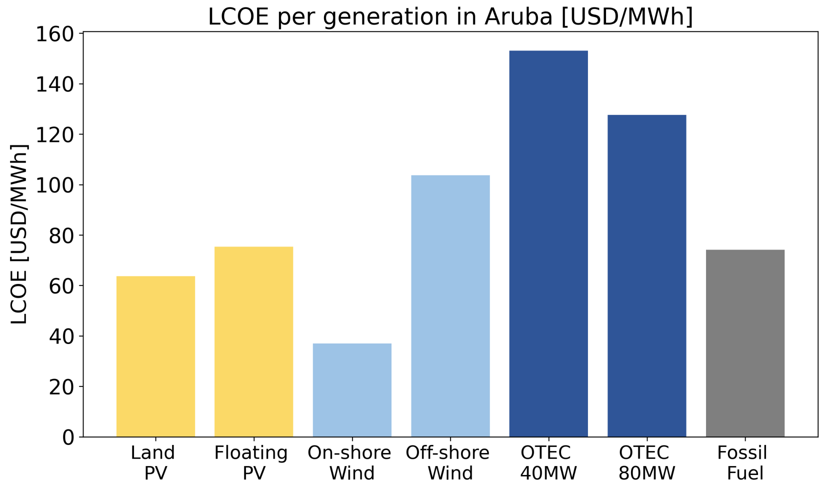


Figure 5.27: LCOE per technology without battery storage.

As indicated in Figure 5.27 land PV and onshore wind have the lowest LCOE, primarily due to their lower Capex and Opex costs. This can largely be attributed to the less complex and more accessible onshore environments in which these installations are constructed, which present fewer technical and logistical challenges, thus lowering the associated costs [92]. Furthermore, onshore RETs currently benefit from more extensive research and development compared to their offshore counterparts.

The LCOE for fossil fuel-based generation in Aruba is observed to be relatively high, primarily due to the elevated costs associated with importing fossil fuels to the island. As Aruba lacks fossil fuel resources, it must import these fuels such as heavy fuel oil and LNG at comparatively high prices [138].

OTEC exhibits the highest LCOE among the assessed energy generation technologies. However, it is crucial to consider that OTEC systems provide baseload capacity. This attribute is particularly valuable in a fully renewable energy system, where balancing intermittent sources like solar and wind requires robust storage solutions that introduce additional costs. The impact of the costs of a BESS with a power capacity of 155MW and storage capacity of 3 GWh on the overall energy system is presented in Figure 5.28. The additional storage costs required to ensure a robust energy system significantly impact the overall system cost, suggesting that OTEC could be cost-competitive within a fully renewable energy system.

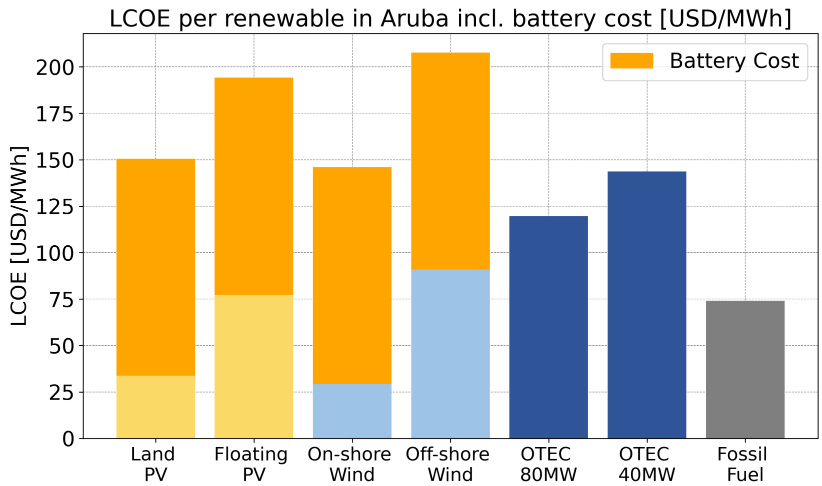


Figure 5.28: LCOE per technology with battery storage.

5.4. Conclusions

To conclude, the techno-economic analysis presents three key takeaways.

Firstly, most of Aruba's renewable energy resources can be found offshore. This is due to the relatively small size the island, of which a large amount is already occupied by protected nature zones or is already inhabited. Moreover, the island benefits from a relatively large offshore EEZ as a result of its fully encompassing coastline bordering the ocean.

Secondly, in Aruba, both wind and solar resources exhibit a significant reduction during September to November, a phenomenon known as ”dunkelflaute”, a period characterised by low wind and solar energy availability. This reduction necessitates substantial battery energy storage capacity to maintain energy supply in a fully renewable system reliant solely on wind and solar resources. Given the high costs associated with large-scale battery systems, alternative renewable technologies such as OTEC may offer a more economically viable solution for achieving a 100% renewable energy system in Aruba.

Thirdly, the cheapest renewable resources can be found onshore. However, when accounting for the storage costs required in a 100% renewable energy system, the total system costs for onshore technologies and an 80+ MW OTEC plant become comparable. To determine the most cost-effective option, a power system modelling analysis is necessary.

6
Power System Modelling

In this chapter the results of the power system modelling are presented, first for the reference scenario in Section 6.1, then for the alternative scenarios in Section 6.2. The technical and economic results across all alternative scenario are presented in 6.2.1 and 6.2.2, followed by a more detailed description per scenario in 6.2.3. Lastly, the main conclusions are summarised in Section 6.3.

6.1. Reference Scenario

For the reference scenario the assumptions as described in Section 4.2 are employed in the Calliope model. It is important to emphasise that for the reference scenario it is assumed that full scale commercial OTEC is available, with the accompanying projected reduction in costs as described in Langer et al. [128]. Three separate cases have been run; one for each of the years 2030, 2040 and 2050. The inputs that change per year are related to costs and demand as described in Section 4.2.

To visualise the fully renewable power system, the capacity of each technology in the power system and total electricity generated per year is presented for each of the three reference scenario years in Figures 6.1 and 6.2.

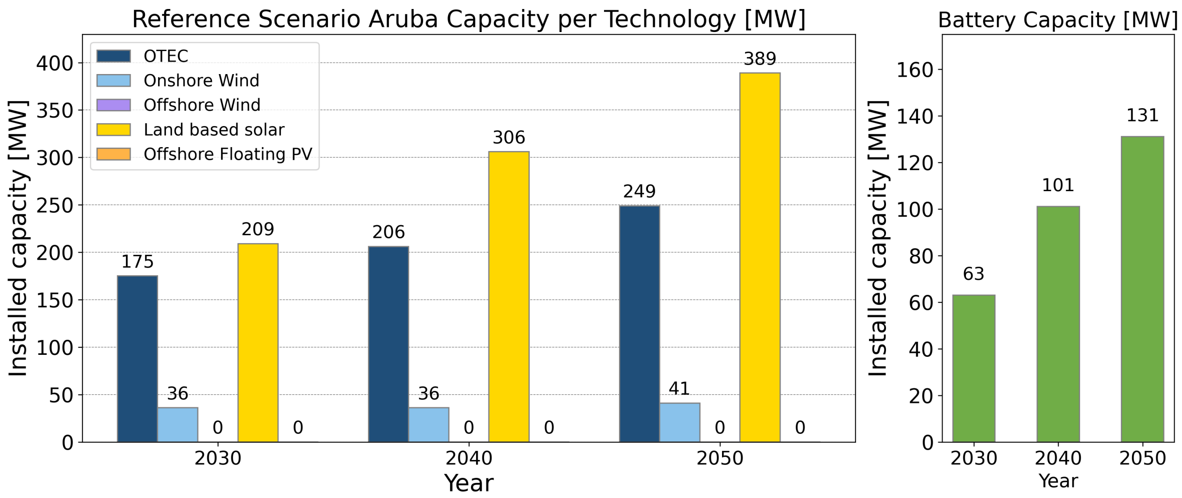


Figure 6.1: Reference scenario installed capacity per technology.

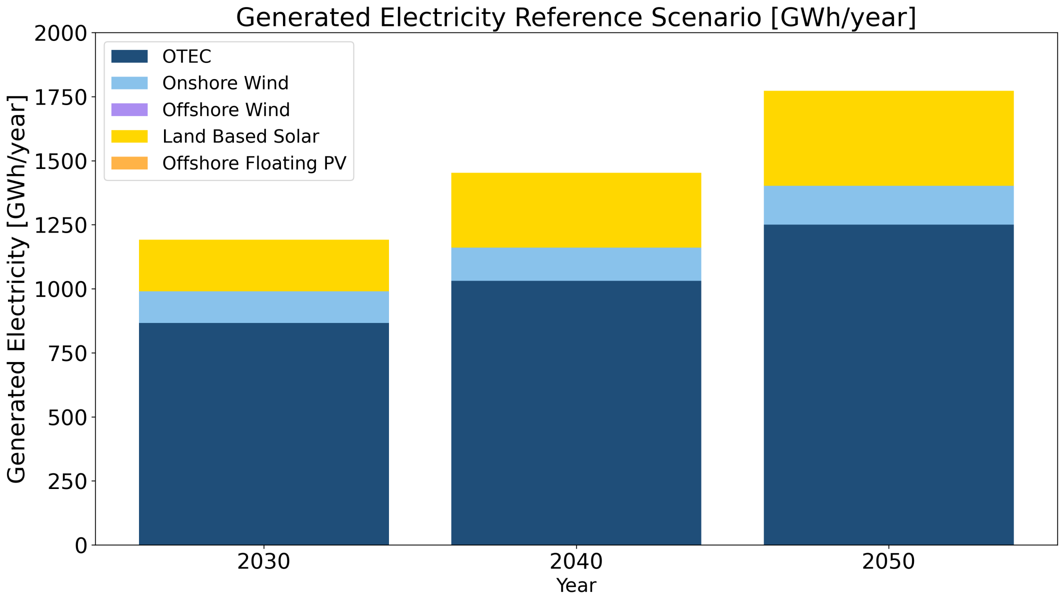


Figure 6.2: Reference scenario yearly generated electricity per RET.

As can be observed in Figures 6.1 and 6.2, OTEC plays a substantial role in the energy system with the cost-optimal installed capacity of 249 MW generating 1,250 GWh in 2050. Besides OTEC, land based solar and onshore wind are deployed by the model. Land based solar is the dominant technology next to OTEC, reaching its maximum capacity of 389 MWp in 2050 and producing 371 GWh of electricity per year. Onshore wind is not deployed to its maximum capacity reaching only 41 MW in 2050 and generating a moderate 152 GWh of electricity per year. This relatively moderate deployment of wind, compared to the substantial deployment of OTEC, is explored further on in this chapter. Both offshore wind and floating PV are not deployed by the model. The total electricity produced during the year in percentages per technology is displayed in Figure 6.3.

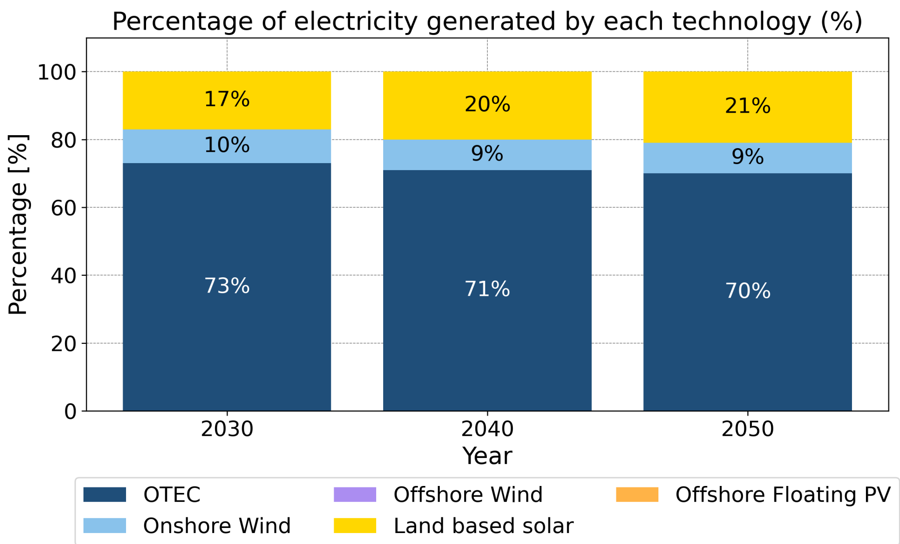


Figure 6.3: Reference scenario electricity produced per RET in %.

OTEC generates a large share of at least 70% of the system's total electricity demand decreasing slightly from 2030 to 2050. This decrease appears to be due to the increase in solar technology in the system, which is likely driven mainly by the decrease in land based utility solar and battery costs.

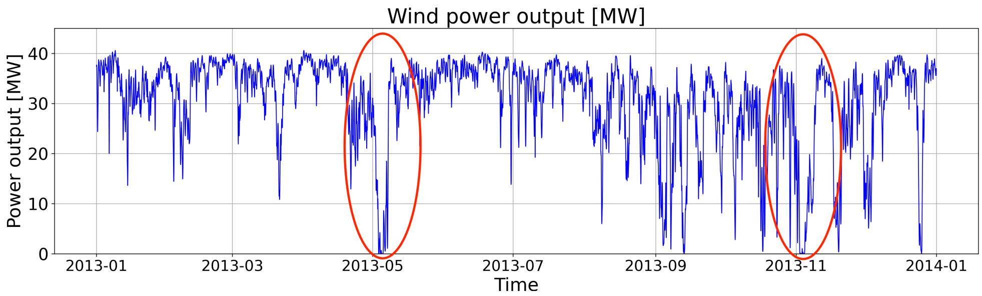
The utilisation factors per technology (Equation 4.4) for the three reference years are presented in Table 6.1.

Table 6.1: Utilisation factor per technology in the reference scenario.

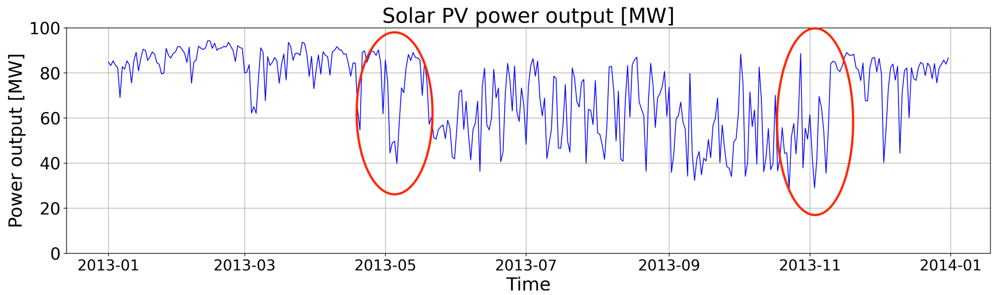
Utilisation Factors per Technology	OTEC	Onshore Wind	Offshore Wind	Land based PV	Offshore Floating PV
2030	81%	53%	-	60%	-
2040	82%	56%	-	60%	-
2050	82%	57%	-	60%	-

The utilisation factor of OTEC is constant over the reference years varying between 81% and 82% and is about 82% in 2050. Furthermore the utility factor for solar stays constant at 60%, whereas wind shows signs of a slight increase, most likely to meet the increase in demand with relatively little extra cost in the form of operational costs.

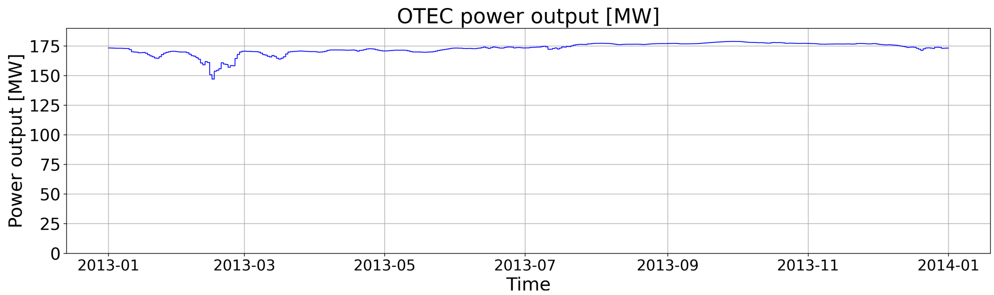
The resulting OTEC capacity in the system is notably high compared to existing 100% renewable system modelling literature exploring Réunion and Indonesia [56, 77, 79]. This discrepancy is likely due to the fact that these case studies have access to other renewable baseload sources or energy storage options, such as geothermal and PSH, which are not available in Aruba. To investigate the significantly high share of OTEC in the system attention is paid to the wind and solar power output during the year. An overview of the power output for onshore wind, utility scale land based solar and OTEC is presented in Figure 6.4 together with the demand profile.



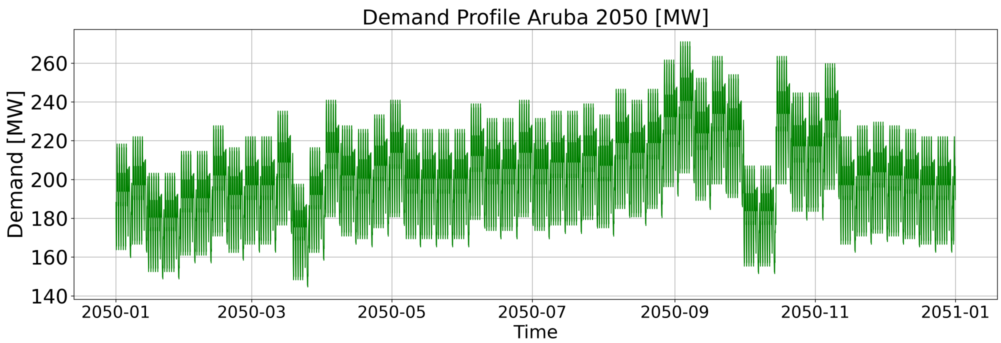
(a) Onshore wind power output.



(b) Land based utility scale solar PV power output.



(c) OTEC power output.



(d) Demand profile Aruba 2050.

Figure 6.4: Power output comparison onshore wind, land based PV, OTEC and demand.

As illustrated in Figure 6.4, there are several instances throughout the year when both solar and wind power generation simultaneously decrease due to reductions in solar and wind resources. The most notable decreases occur in May and early November (highlighted in red), as well as during a prolonged period with less distinct dips between September and December. Analysis of the 1980 to 2023 period indicates that these "dunkelflaute" events are recurrent, particularly between September and November. The period between September and November is historically known for low wind resources [110]. However, the observed reduction in solar resources during this period is not well documented in literature. The decrease in solar output in November is likely related to increased rainfall in Aruba later in the year, peaking in November [190]. In contrast, OTEC consistently maintains stable power output throughout these periods.

During these periods of dunkelflaute, the model is presented with two options: either the implementation of OTEC as a baseload power source or the deployment of large-scale storage technologies, in this case BESS, to meet demand. Based on current cost assumptions, the model suggests that OTEC is the more economically viable option for achieving a 100% renewable energy system, and selects OTEC to supply the necessary capacity. Additionally, a comparison with demand patterns reveals that this reduction in renewable generation coincides with a period of above-average demand during the first two weeks of November, exacerbating the impact of the dunkelflaute event.

Observing the economics of the system, the levelised cost of the system and the LCOE per supply technology are presented per year in Table 6.2.

Table 6.2: LCOE per technology and LCoS for reference scenarios.

LCOE [USD/MWh]	OTEC	Onshore Wind	Offshore Wind	Land based solar	Offshore Floating PV	**LCoS**
2030	131	44	-	60	-	120
2040	118	37	-	53	-	108
2050	106	33	-	45	-	96

A decrease in the LCoS from 2030 all through 2050 is observed in Table 6.2. This decrease is to be expected as the costs of the supply technologies employed have been programmed to decrease over time due to technological learning. It is worth noting that residential electricity rates in Aruba are currently 0.21 USD per kWh, with commercial and industrial rates being higher [191]. However, to make a meaningful comparison, additional costs related to transmission and distribution and profit margins must be considered. The LCoS will be used in the subsequent section to compare the generation costs across various scenarios.

An interesting finding is that, despite the lower LCOE of onshore wind compared to land-based solar and OTEC, it is deployed the least in the system. This is likely due to the less consistent intermittent nature of wind resources, compared to solar resources, which leads to longer periods of low availability. As a result, larger BESS are required, increasing storage capacity needs and overall system costs. Since the model optimises for system cost, wind is likely deployed less frequently for this reason. This finding underscores a limitation of relying solely on LCOE comparisons, which will be discussed further in the discussion section.

6.2. Alternative Scenarios

For the alternative scenarios the year 2050 is considered as it is projected to be the most likely year when large-scale OTEC could become commercially available in Aruba. The results of these alternative scenarios are compared to those of the reference scenario in 2050, presented in Section 6.1.

6.2.1. Technical Results

The amount of OTEC capacity deployed by the model in all scenarios is presented in Figure 6.5. OTEC is present in almost all scenarios, except for the 10 MW OTEC plant, 0 MW OTEC and no fossil fuel restriction scenarios. In all the other scenarios OTEC is installed with a capacity of at least 180 MW. An overview of the deployed capacity and annually generated electricity per technology in each scenario is presented in Figure 6.6.

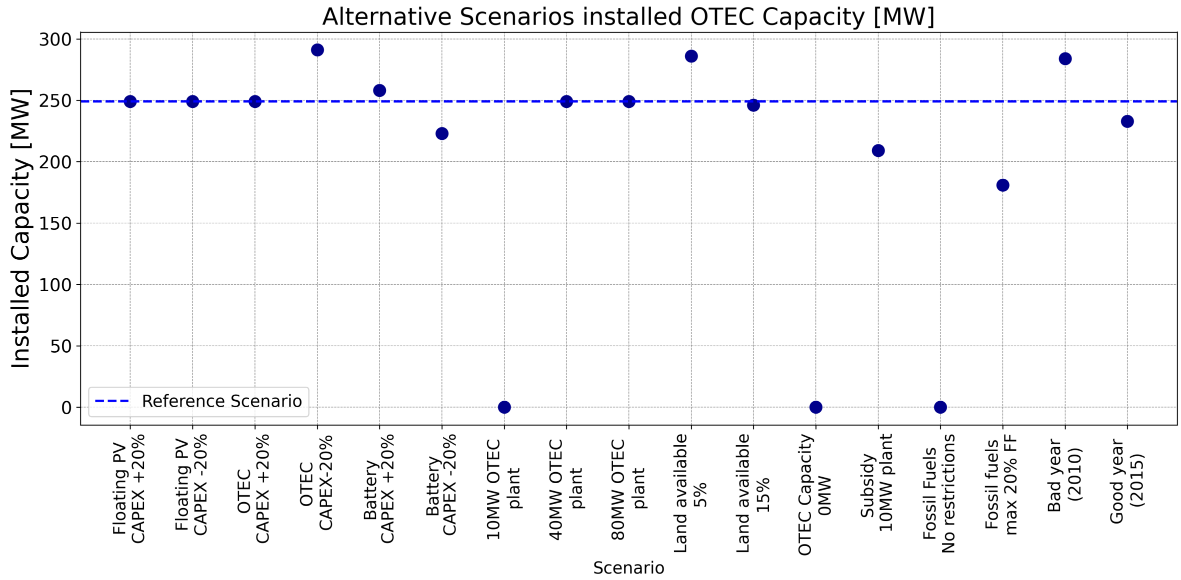


Figure 6.5: OTEC Capacities deployed in alternative scenarios in 2050.

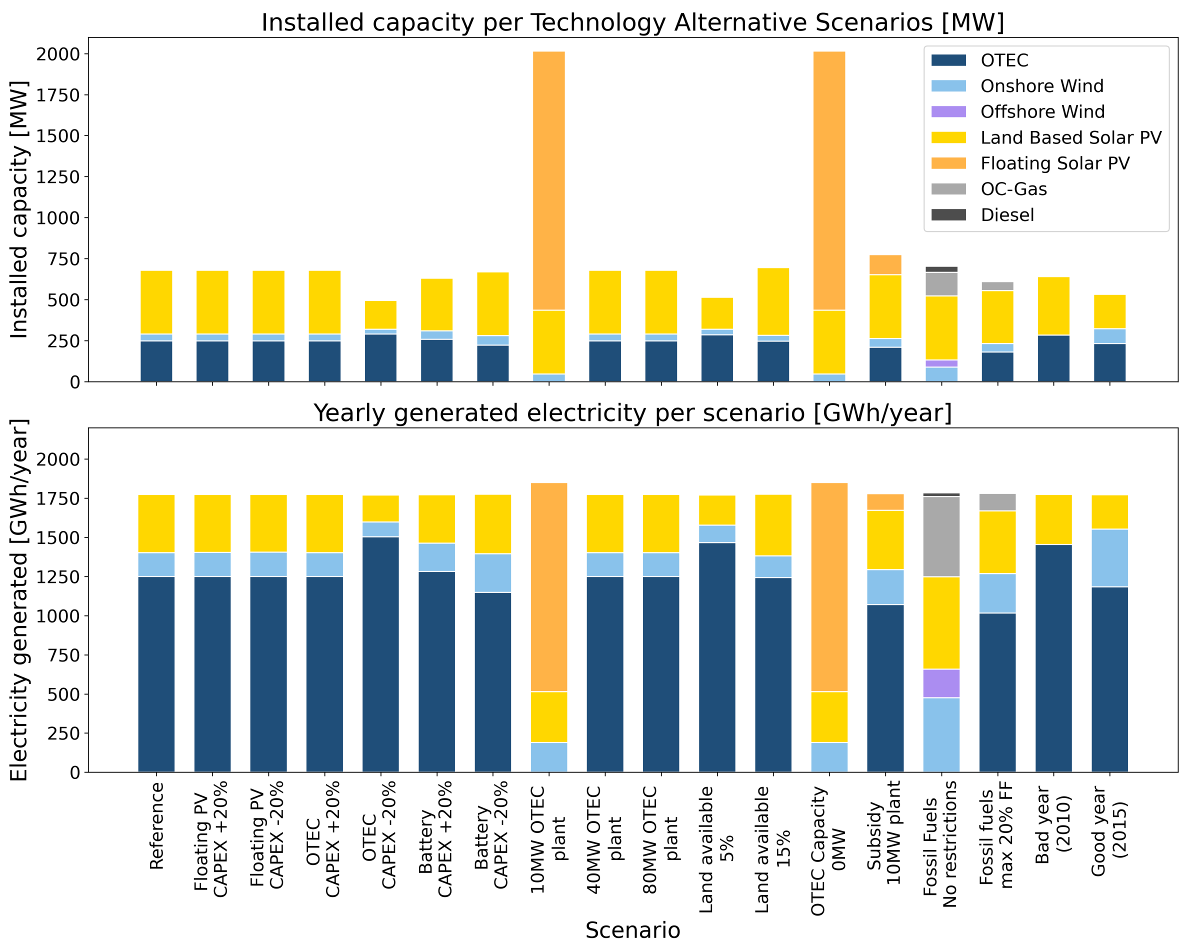


Figure 6.6: Capacities deployed and electricity generated per year in alternative scenarios.

The capacity and yearly generated electricity of the generation technologies are presented in Figure 6.6. The most favoured generation technology is land based solar PV. In a large number of the scenarios the model utilised all the available land based solar PV, 389 MWp. In addition to land-based PV, OTEC appears to be consistently deployed. However, in the 10 MW OTEC plant and OTEC 0 MW capacity scenario OTEC is not deployed, being substituted for about 1500 MWp Floating PV capacity combined with BESS, with a capacity of 600 MW and an energy storage capability of 2400 MWh. This suggests there is a ”tipping point” where OTEC is replaced by floating PV combined with BESS. This tipping point is strongly correlated with the cost of BESS due to the large amount of storage that would be required to provide electricity during the dunkelflaute periods described in Section 6.1 and the cost of floating PV.

In almost all cases onshore wind is installed, however the model does not deploy the maximum technical potential of the technology on Aruba. Offshore wind is never installed except for the scenario where there are no restrictions on fossil fuels. In the scenario where fossil fuels are permitted with no restrictions, onshore wind is deployed to its maximum capacity and offshore wind is installed with a capacity of 44 MW. In this scenario land based PV is deployed to its maximum capacity but notably floating PV and OTEC are not deployed. This suggests that fossil fuel restrictions significantly influence whether wind or solar is deployed in the system, with wind being preferred over solar in the case of no restrictions.

This may be due to the more variable nature of wind resource availability. Furthermore, OC-gas and diesel generators offer operational flexibility, allowing them to be turned on and off as needed to meet demand. In contrast, OTEC has a baseload profile assigned to it. This characteristic may cause the model to prioritise OTEC as a baseload option, potentially blocking the deployment of other RETs, such as wind in cases where fossil fuel options are limited. When dispatchable fossil-fuel generators are available, the model appears to have greater flexibility in selecting technologies.

Adjusting the costs of OTEC, floating PV and batteries by 20% does not significantly alter the deployment mix, suggesting that the system exhibits low sensitivity to cost fluctuations. This outcome is likely attributable to the substantial battery capacity required when reducing OTEC’s share in the system (as depicted in Figure 6.7), which leads to considerable additional costs.

The resulting battery storage capacity is presented in Figure 6.7. Battery storage is present in all scenarios. Its function ranges from operating as a backup electricity supply to being the backbone of the energy system. In the case of large OTEC implementation, battery storage is deployed with a capacity of about 100 MW. Whereas without OTEC the battery storage is scaled up to about 600 MW.

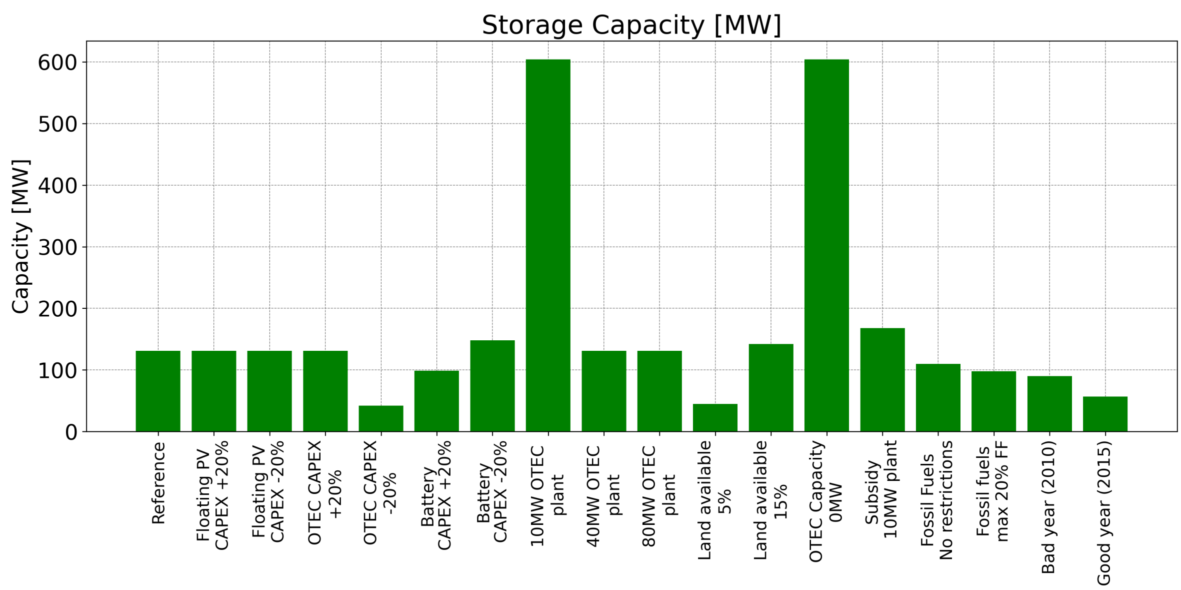


Figure 6.7: Battery storage deployment in alternative scenarios.

6.2.2. Economic Results

The levelised cost of the system of all scenarios is presented in Figure 6.8. The cost of the system varies between 71 USD/MWh and 150 USD/MWh with one of the cheapest scenarios with 100% renewables being the reference scenario with an LCoS of 96 USD/MWh (excluding the scenarios where OTEC's Capex is 20% cheaper). The system cost is lowest in the scenario with no restrictions on fossil fuels, in which case a mix of mainly gas and some diesel in combination with land based solar and onshore and offshore wind is presented as the cheapest scenario.

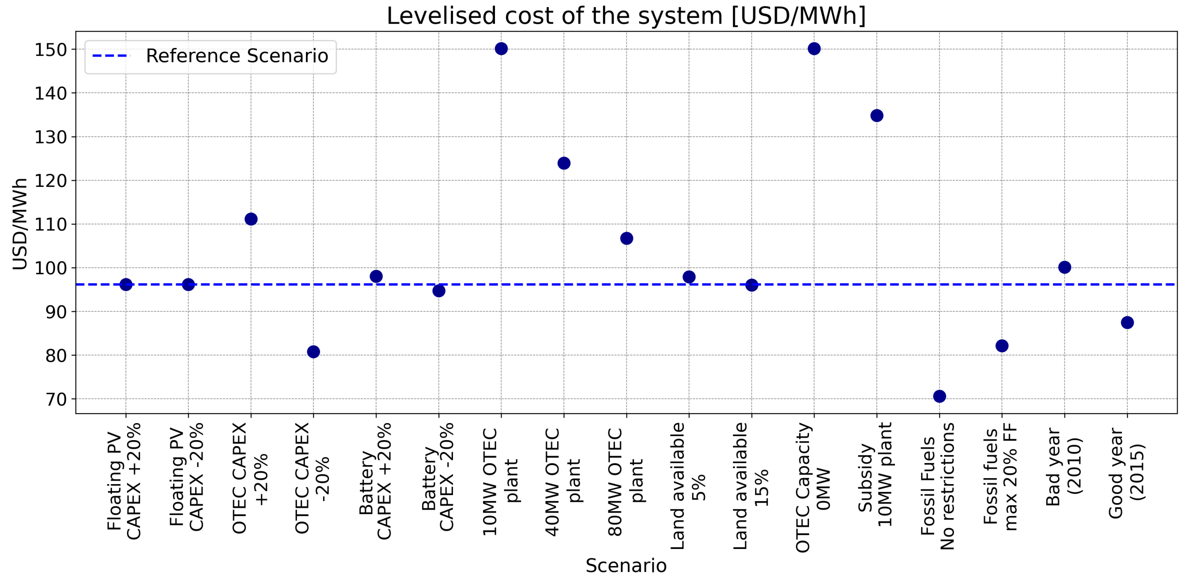


Figure 6.8: Levelised cost of the system of alternative scenarios.

This suggests that for a fully renewable system, the reference scenario offers one of the most favourable economic outcomes. However, it is observed that the inclusion of fossil fuels further reduces the LCoS, indicating that transitioning to a fully renewable system may not be as economically viable as maintaining a proportion of fossil fuels within the generation mix. Consequently, to transition to a fully renewable system it may become necessary to promote the adoption of RETs in Aruba through future financial incentives, either from local government initiatives or potentially from international organisations and entities.

However, it is important to consider that the model does not incorporate potential additional costs related to greenhouse gas emissions in the future, which could introduce additional expenses in electricity generation from fossil fuels. Furthermore, the model assumes constant prices for gas and diesel, an assumption that does not reflect real-world conditions. In reality, prices for these resources can fluctuate significantly due to global shortages triggered by events such as wars or economic turmoil, leading to price volatility and potentially higher operational costs.

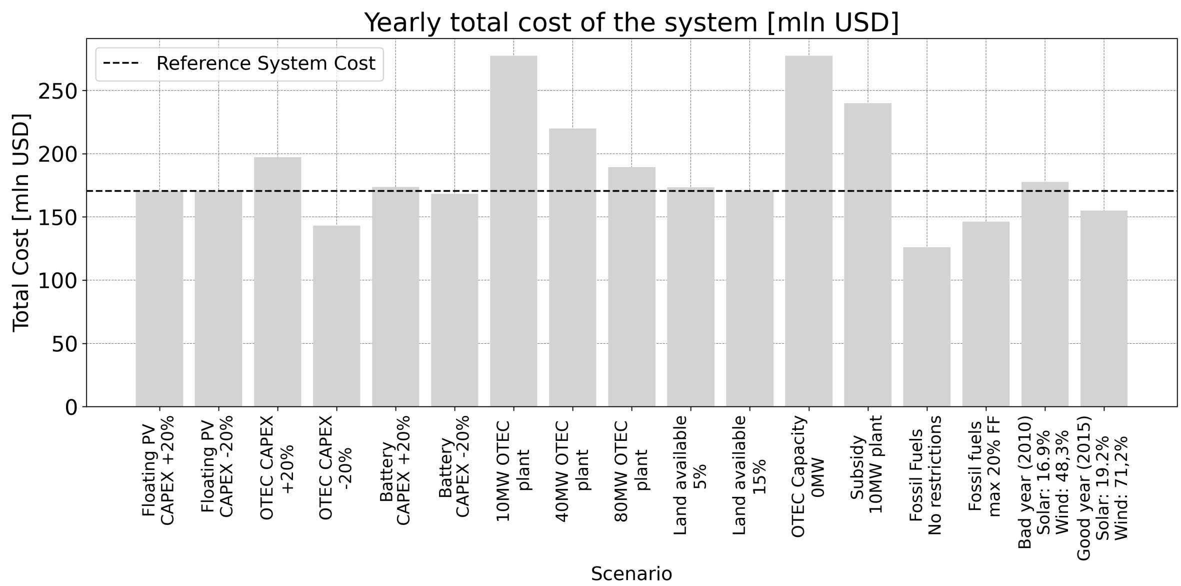


Figure 6.9: Total system costs for the alternative scenarios.

In Figure 6.9 the total yearly costs of the entire system in 2050 (including levelised cost of Capex) are presented. The system cost of the reference scenario is noted with the dark grey dashed line. Apart from the cost range scenarios, the system costs are lower with the inclusion of fossil fuels and with better weather conditions. All the scenarios without OTEC (save from the fossil fuel scenarios) are more expensive than with OTEC.

The reference scenario's total annual cost is approximately 170 million USD, whereas the scenario without OTEC is estimated to cost approximately 277 million USD, i.e. 107mln USD higher than the reference scenario. The scenario with no limitation on fossil fuels results in an estimated 126 million USD, 44 million USD less than the 100% renewable reference scenario. Set against Aruba's GDP of 4.0 billion USD [18], these are not insignificant amounts.

6.2.3. Detailed Results per Scenario

The results for each alternative scenario are presented in detail here, along with an analysis of more nuanced findings.

Cost Sensitivity

The supply technology installed capacity per cost sensitivity scenario is presented in Table 6.4.

Table 6.3: 2050 cost sensitivity scenario output.

Cost Sensitivity 2050		OTEC [MW]	OTEC LCOE [USD/MWh]	LCoS [USD/MWh]	OTEC Utilisation Factor [%]
Floating PV	CAPEX +20%	249	106	96	82.4
	CAPEX -20%	249	106	96	82.4
OTEC	CAPEX +20%	249	127	111	82.4
	CAPEX -20%	291	82	81	85.0
Battery	CAPEX +20%	258	107	98	81.6
	CAPEX -20%	223	104	95	84.5

Table 6.4: Capacity per technology for 2050 cost sensitivity scenario.

Capacity per Technology [MWh]		OTEC	Onshore Wind	Offshore Wind	Land Based Solar PV	Floating Solar PV
Floating PV	CAPEX +20%	249	41	-	389	-
	CAPEX -20%	249	41	-	389	-
OTEC	CAPEX +20%	249	41	-	389	-
	CAPEX -20%	291	29	-	175	-
Battery	CAPEX +20%	258	52	-	321	-
	CAPEX -20%	223	58	-	389	-

OTEC has significant installed capacity in the system in all the cost sensitivity scenarios. Observing the effects of the cost changes, lowering offshore floating PV Capex does not impact OTEC capacity. A decrease larger than 20% is necessary to get floating PV in the energy mix. Additionally, with a 20% higher OTEC Capex the OTEC installed capacity and utilisation remain the same as the reference case. This appears to indicate that unless floating solar or BESS technology gets substantially cheaper that OTEC at commercial scale is necessary for a fully renewable energy system in Aruba.

With 20% lower OTEC Capex, there is an increase in OTEC installed capacity (+17%) and utilisation. 20% changes in battery Capex do affect the OTEC installed capacity: with lower battery costs, OTEC installed capacity is reduced by 10% compared to the reference case and with higher battery costs it is increased by 4%. It appears that the combination of more onshore wind and batteries is most competitive for OTEC at the margin. Hence, OTEC installed capacity is sensitive to changes in battery costs. Interestingly, the utilisation factor for OTEC reduces as its installed capacity increases in this situation (and vice-versa it increases with a capacity reduction), i.e. with more OTEC capacity installed (to balance a system with fewer batteries), the lower the OTEC utilisation. From a project economics perspective a high utilisation factor is preferred. If the utilisation factor is not high enough a payment system based on installed capacity rather than generated energy would likely be required. Known as a ”take or pay” contract this would ensure that the electricity that is available to be produced by the OTEC facility is paid for, whether it is deployed or not.

OTEC Plant Sizes

The results from the OTEC plant sizes scenario are shown in Table 6.5.

Table 6.5: 2050 OTEC Plant sizes scenario output.

OTEC Plant Sizes 2050		OTEC [MW]	OTEC LCOE [USD/MWh]	LCoS [USD/MWh]	OTEC Utilisation Factor [%]
OTEC plant size	10MW$_{gross}$	0	-	150	-
	40MW$_{gross}$	249	146	124	82.4%
	80MW$_{gross}$	249	121	107	85.0%

At a plant size of 10 MW OTEC does not get implemented in the system in 2050. However, at a size of 40 MW OTEC is deployed. After analysing the results it is found that the model implements OTEC when the plant size is 35 MW or larger. It is noted that when OTEC is included in the system it is deployed at a large scale, 249 MW in the case of 40 and 80 MW.

There appears to be nearly no effect on the system when the plant size is increased to 80 MW except for a decrease in LCOE and LCoS, due to the lower OTEC costs. The fact that not more OTEC capacity is installed from 40 to 80 MW appears to indicate a type of "cut off point". It is assessed that at this point there is no more room for land based solar to grow due to its technical capacity limitation and that more onshore wind or floating PV capacity (together with increased BESS) is more expensive than OTEC which results in no further wind or floating PV capacity being installed. As a result OTEC is the cheapest option and therefore chosen.

This analysis suggests that OTEC is economically viable for a fully renewable energy system in Aruba when implemented at a commercial scale exceeding 35 MW. For OTEC facilities with capacities below this threshold, financial assistance is crucial in achieving economic viability. Given that OTEC technology is still in the pre-commercial phase, these findings underscore the necessity for support mechanisms that can facilitate the transition to commercial viability. Such support would enable economies of scale and technological advancements to render OTEC economically feasible.

Technical Capacity Limitations

The results of the technical capacity limitations scenario cases can be found in Table 6.6 and 6.7.

Table 6.6: 2050 Technical Capacity Limitations scenario output.

Technical Limitations 2050		OTEC [MW]	OTEC LCOE [USD/MWh]	LCoS [USD/MWh]	OTEC Utilisation Factor [%]
Technical Limitations	Land available 5%	286	104	98	84.4%
	Land available 15%	246	106	96	82.9%
	OTEC Capacity 0MW	0	-	150	-

Table 6.7: Generated electricity per technology in the technical limitations scenario.

Capacity per technology [MW] 2050		OTEC	Onshore Wind	Offshore Wind	Land Based Solar PV	Floating Solar PV
Technical Limitations	Land available 5%	286	34	-	195	-
	Land available 15%	246	37	-	412	-
	OTEC Capacity 0MW	-	44	-	389	1,781

As can be observed in Table 6.6, when land availability is decreased to 5%, instead of 10%, the amount of OTEC capacity in the system increases to 286 MW. When the amount of land available is increased to 15%, an interesting finding is that the system doesn't use all the possible land based solar capacity (only 412 MW out of the maximum of 584 MW). This appears to indicate that the battery cost is a very important element in determining the amount of OTEC in the system.

These findings suggest that the costs of building a BESS large enough to facilitate a fully renewable energy system, even with cheaper land based solar, is higher than that of a system including commercial scale OTEC.

Subsidies

The results of the subsidy scenario can be found in table 6.8.

Table 6.8: Capacity and generated electricity per RET with a 10MW OTEC plant and 15% subsidy.

Subsidy 10MW 15%	OTEC	Onshore Wind	Offshore Wind	Solar	Floating Solar
Capacity [MW]	209	54	-	389	123
Generated electricity [GWh]	1,071	223	-	379	107

As the subsidy is gradually increased, the model begins deploying a 10 MW OTEC plant at a subsidy rate of 15%. In this scenario, onshore wind capacity also increases compared to the reference case, likely because OTEC remains relatively expensive, making the combination of wind and battery storage more cost-effective. Additionally, 123 MWp of floating solar is deployed, likely for the same reason as the increase in onshore wind capacity. To accommodate the higher share of intermittent technologies, the BESS capacity is also slightly increased.

Fossil Fuel Phase-out

The results of the fossil fuel phase out scenario cases can be found in Tables 6.9, 6.10 and 6.11.

Table 6.9: 2050 Fossil Fuel Phase-out scenario output.

Fossil Fuel Phase-out 2050	OTEC [MW]	OTEC LCOE [USD/MWh]	LCoS [USD/MWh]	OTEC Utilisation Factor [%]
Fossil Fuels: No Restrictions	0	-	70	-
Fossil Fuels: Max 20% FF	180	95	82	92.4%

From Table 6.9, it is evident that the inclusion of unrestricted Fossil Fuels leads to no OTEC being present in the system. It is interesting to note that in this case onshore and offshore wind as well as land based solar are included in the system, as can be seen in Table 6.10 below. As the levelised cost of the system is slightly lower than that of the 2050 reference case, it is evident that for OTEC to succeed in the future either subsidies on OTEC, some restrictions on fossil fuels or an increase in fossil fuel costs is essential.

Table 6.10: Installed capacities under different fossil fuel scenarios.

Capacity [MW]	OTEC	Onshore wind	Offshore wind	Land Based PV	Floating PV	OC-Gas	Diesel	Battery
No Fossil Fuel Restrictions	0	89	44	389	0	145	36	110
Max 20% Fossil Fuels	181	52	0	322	0	55	0	98

Another noteworthy finding from Table 6.9 is that in the case of the maximum 20% fossil fuel case, OTEC still plays a significant role in the energy system with a capacity of 180 MW. It is found that for a fossil fuel allowance of up to about 50%, OTEC is included at large enough scale that its LCOE would be cost competitive. Above 50% fossil fuel allowance the OTEC capacity dips below 40 MW, ref Table 6.11 below, which results in higher Capex costs per MWh and poorer economic performance as shown in Table 6.5.

Table 6.11: 2050 OTEC Capacity at different Fossil Fuel capacity maxima.

FF Capacity max	10%	20%	30%	40%	50%	60%	80%	90%	100%
OTEC Capacity [MW]	210	180	150	103	57	22	6	0	0

Solar and Wind Resources

The results of the solar and wind resources scenario are presented in Table 6.12.

Table 6.12: Solar & Wind resources scenario output.

Solar & Wind resources 2050	OTEC [MW]	OTEC LCOE [USD/MWh]	LCoS [USD/MWh]	OTEC Utilisation Factor [%]
Low resource availability	284	104	100	84.3%
High resource availability	233	105	87	83.6%

As can be observed in Table 6.12, in both the good and bad year scenario OTEC has a significant presence in the system. It has a capacity of 284 MW in a year with bad solar and wind resources and 233 MW in a year with good solar and wind resources. The quality of wind and solar resources does appear to have some effect on the amount of installed OTEC capacity, varying OTEC capacity by +14% and -7%. In either case, OTEC is present at a large enough scale to make it cost competitive.

6.3. Conclusions

To conclude, it is found that OTEC has the potential to become a large component in Aruba's energy mix with the reference scenario consisting of 249 MW of OTEC in 2050.

Furthermore, OTEC demonstrates a significant presence across a majority of the evaluated scenarios, suggesting its potential role in a wide range of future scenarios. Crucially, the scalability of OTEC technology is essential for its economic viability. This is exemplified in the 10 MW OTEC scenario, where the technology fails to remain economically advantageous. Economic feasibility without subsidies is achievable only at larger scales, necessitating a minimum capacity of 35-40 MW for the plants. A subsidy of at least 15% is required to make a 10 MW OTEC plant cost effective in the system.

Including OTEC in the fully renewable energy system in 2050 lowers the levelised cost of the system from 150 USD/MWh to 96 USD/MWh in the case of the reference scenario. The reference scenario's total annual cost is approximately 170 million USD. This would save approximately 107 million USD per year compared to a fully renewable system without OTEC. Set against Aruba's GDP of some 4.0 billion USD per year these are not insignificant amounts.

It is observed that OTEC and solar PV are the dominant generators, with wind only becoming significant when fossil fuels are introduced to the system. This observation can be attributed to the greater volatility of wind energy compared to solar PV systems, which necessitates increased battery storage capacity and consequently results in higher associated costs.

Lastly, OTEC might be restricted through its utilisation, which is observed to be between 81-82% in the reference case. This could impact the project profitability and therefore needs to be considered further when formulating a plan for OTEC implementation, for example by considering payment for capacity availability rather than generated energy.

7
Stakeholder and Institutional Analysis

In this chapter the result of the stakeholder analysis are presented in Section 7.1. This is followed by the PESTEL analysis findings in Section 7.2 and the identified key stakeholders for implementation in Section 7.3. Lastly, a roadmap investigating OTEC's implementation in Aruba is presented in Section 7.4.

7.1. Stakeholder Analysis

In this section the results of the stakeholder analysis are presented. Firstly, the identified stakeholders are presented in Section 7.1.1. This is followed by an overview detailing the interactions among these stakeholders within the stakeholder network in Section 7.1.2.

7.1.1. Identified Stakeholders

The stakeholders are broadly categorised in social actor groups according to Verbong and Geels [140]: government, market and society. In this work government is further divided into local government and international governmental bodies and the category Knowledge Institutes is incorporated. An overview of the categories is provided below.

1. Market: stakeholders operating in commercial markets. This includes but is not limited to the electricity sector in Aruba.
2. Local Government: the Government of Aruba, which consists of ministries and is further divided into departments.
3. International Governmental Bodies: governmental bodies other than the government of Aruba such as the Government of the Netherlands and the European Union.
4. Society: stakeholders in Aruba that don't operate in the market or government but could affect the implementation of OTEC through support or resistance.
5. Knowledge Institutes: stakeholders that are active in OTEC research through experimental OTEC setups and theoretical research with as goal to contribute to the current knowledge of OTEC.

The stakeholders are presented per social actor group. For a more detailed description and examples of individual actors refer to Appendix D.

Market

Electricity and Utility Companies Aruba

In Aruba the electricity sector is characterised by three state owned companies, who are responsible for the generation and distribution of electricity. These three companies are:

- WEB Aruba N.V.: primarily producer of electricity (and drinking water) in Aruba. To supply these services, it operates generation facilities and desalination plants.

- N.V. Elmar: responsible for the distribution and retail of electricity throughout Aruba. This includes the installation and maintenance of the electricity distribution network as well as electricity sales and services to customers.
- Utilities Aruba N.V.: is the holding company of both WEB and Elmar, as is illustrated in Figure 7.1. It is solely owned by the government of Aruba, coordinating between both organisations to ensure seamless operation and management of electricity and water services. Additionally, it oversees a strategy of the sustainable energy transition [83].

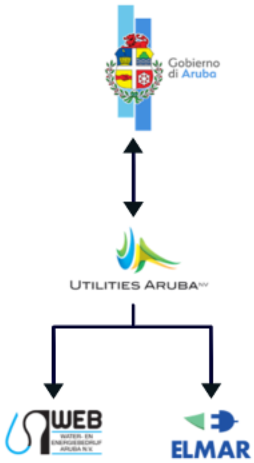


Figure 7.1: Overview of Utilities Aruba management structure [192].

OTEC Project Developer

The project developer, typically a large international company, manages the development of an OTEC project, acting as the central coordinator among stakeholders. Their responsibilities include overseeing construction, providing technological expertise, liaising with local electricity companies (WEB, Elmar and Utilities Aruba), securing government approvals and financial backing and potentially operating the plant. While WEB N.V. or Elmar could serve as project developers, their involvement depends on the perceived maturity of the technology. Utilities Aruba, known for its risk-averse approach, tends to delegate the risks of new technologies to external parties [193]. Thus, due to the high initial capital and specialised expertise required for OTEC an *Independent Power Producer* (IPP) is recommended to take on this role.

Technology Advisers

These organisations possess in-house OTEC expertise and experience in designing or building key components like cold water pipes, heat exchangers, pumps, mooring systems, or entire OTEC systems. Although they typically lack the capital to develop large-scale plants, they have experience with smaller plants through involvement with their construction in the past. An example is Makai Engineering, which has been involved in constructing multiple OTEC plants, including a 105 kW facility currently operational in Hawaii [194].

Financial Institutions

Financial institutions, including development banks, commercial banks and investment funds, provide financial products like loans, equity investments and bonds essential for funding high-capital projects like OTEC. These institutions help secure initial capital, structure financial arrangements and offer expertise to enhance project viability and manage risk. Currently, development banks are the most feasible funding sources for OTEC due to its early development stage, but as the technology matures and more projects prove successful, traditional financial institutions, such as commercial banks, are expected to become viable funding options.

Alternative RET Developers

These companies deploy alternative renewable energy technologies in Aruba, including onshore and offshore wind, land-based and floating solar PV and BESS. Operating within the same socio-economic environment as OTEC developers, it remains uncertain to what extent these technologies would compete. Wind and solar PV are intermittent, while OTEC would likely provide baseload power, potentially making them complementary. However, with large-scale BESS, a scenario could emerge where wind, solar PV and BESS together form a 100% sustainable energy solution, eliminating the need for baseload technologies like OTEC and introducing economic competition.

Companies operating near OTEC

While these companies are not directly involved in OTEC development, they may interact with it due to shared offshore environments (e.g., shipping, cruise and scuba diving companies) or concerns related to electricity grid reliability (e.g., the Aruba Hotel and Tourism Association).

Local Government

The government of Aruba comprises eight ministries [195]. Six of these ministries have been identified as having departments that serve as stakeholders during the planning, construction and operational phases of an OTEC project in Aruba. Figure 7.2 provides an overview of the Aruban government and its ministries.

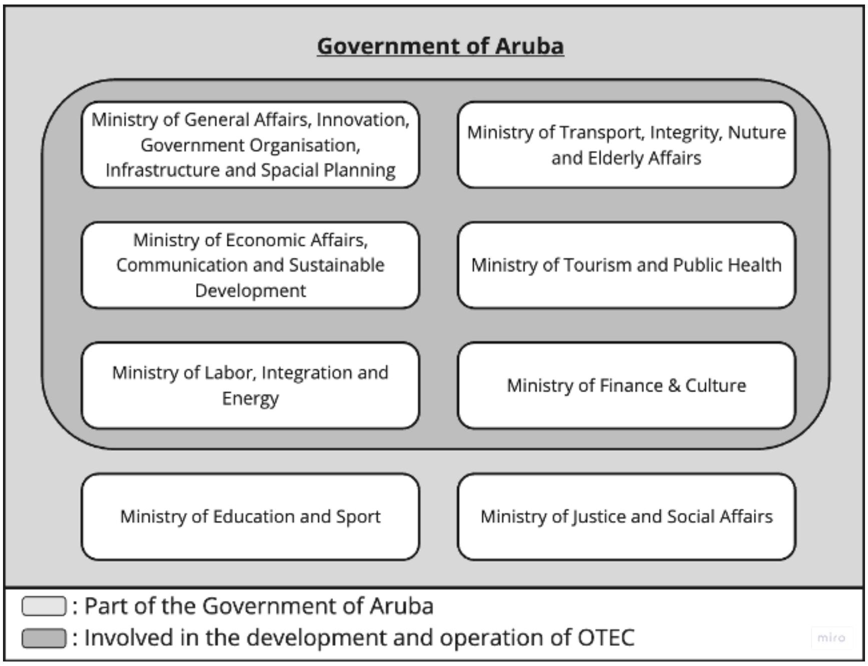


Figure 7.2: Ministries of Aruba involved with OTEC.

Each ministry comprises multiple departments and those that could potentially be actively involved in the OTEC implementation process have been identified. Figure 7.3 provides an overview of these relevant departments and their associated ministries.

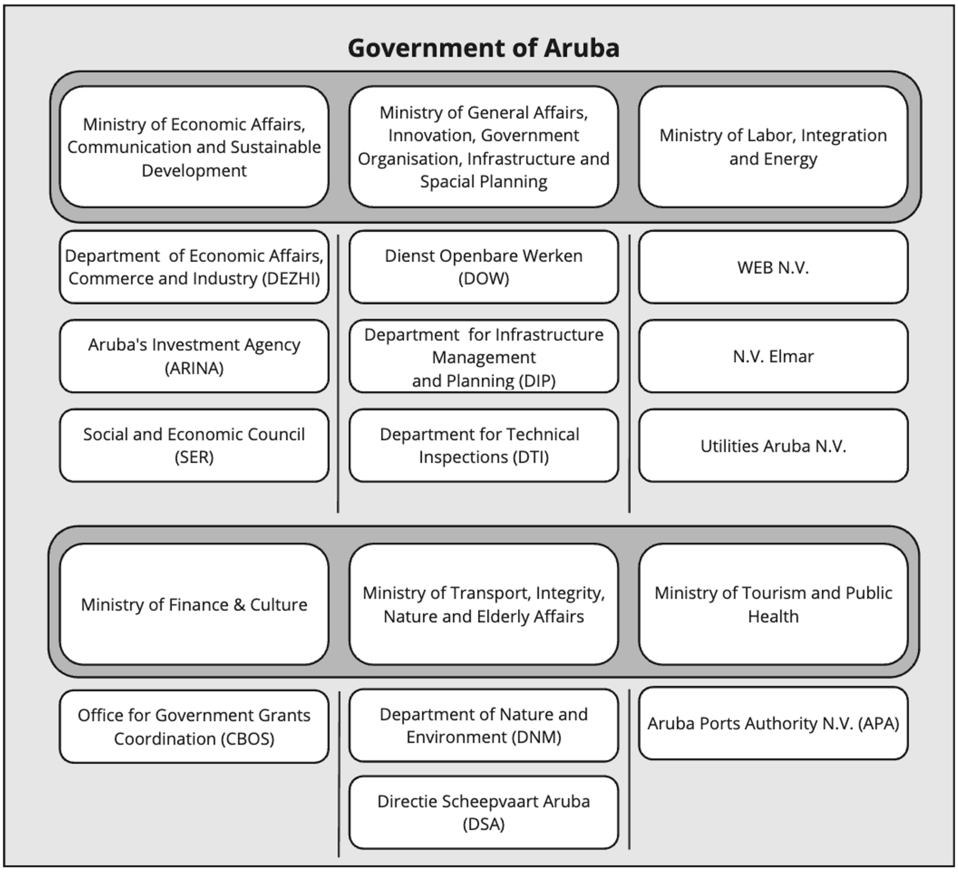


Figure 7.3: Aruban ministerial departments involved with the development and construction of OTEC.

A description of all the departments is provided in appendix D. Here the most important ministries and the respective departments are elaborated upon. Aruba has been in the process of undertaking structural governmental reform since November 2020. This reform is a result of agreements made with the Kingdom of the Netherlands as part of the support package "Landspakket" to aid Aruba in the recovery from the Covid-19 pandemic [196]. As such, this analysis is done with the knowledge that the governmental ministry structure could change in the future.

Ministry of Labor, Integration and Energy

The Ministry of Labor, Integration and Energy oversees the government's involvement in state-owned entities Utilities Aruba, WEB and Elmar, which, although structured and regulated independently, are significantly influenced by the government. A notable example is the LNG project between Eagle LNG and WEB, where government support played a crucial role in its completion [110]. Effective communication and lobbying with the responsible minister are essential for implementing new renewable energy projects like OTEC.

Ministry of Economic Affairs, Communication and Sustainable Development

The Ministry of Economic Affairs, through the *Department of Economic Affairs, Commerce and Industry* (DEZHI), is responsible for issuing permits or concessions for electricity generation and distribution in Aruba. Currently, Elmar holds the sole concession to distribute and sell electricity to consumers. Although WEB was historically the only authorised electricity producer, the establishment of the Vader Piet wind farm in 2009 by NuCapital set a new precedent, allowing other entities to generate electricity and sell it to WEB. Recently, Elmar has also received concessions to generate electricity [197]. This evolving regulatory landscape indicates that it is possible to obtain concessions to generate and sell OTEC-generated electricity to WEB or Elmar. Establishing relationships with the responsible minister is crucial for acquiring the necessary permits for electricity production.

Ministry of General Affairs, Innovation, Government Organisation, Infrastructure and Spatial Planning

Within the Ministry of General Affairs, Innovation, Government Organisation, Infrastructure and Spatial Planning, three key departments are involved: the *Dienst Openbare Werken* (DOW), the *Department for Infrastructure Management and Planning* (DIP) and the *Department for Technical Inspection* (DTI).

DOW and DIP collaborate closely on organising and maintaining Aruba's infrastructure. DOW issues on and offshore building permits, including those required for OTEC plant construction and cable landing points [198], while DIP handles spatial planning and zoning and would need to be consulted on plant location [199]. DTI serves as a regulatory body, certifying access points to the grid, conducting safety inspections and ensuring compliance with standards [200].

Ministry of Transport, Integrity, Nature and Elderly Affairs

Within the Ministry of Transport, Integrity, Nature and Elderly Affairs the *Department of Nature and Environment* (DNM) and *Directie Scheepvaart Aruba* (DSA) are identified as relevant for OTEC's implementation.

The DNM is responsible for protecting Aruba's environment through policy development, research, monitoring and inspections, and oversees onshore and offshore conservation zones managed by the *Aruba Conservation Foundation* (ACF) [201]. Effective communication with the ministry is crucial if OTEC operations intersect with these zones or pose environmental concerns. The DSA, also known as Department of Marine Affairs, manages sea traffic within Aruba's marine sovereignty and must be consulted during OTEC site selection to avoid disrupting trade routes.

International Governmental Bodies

The Government of the Netherlands

Aruba, as a constituent country of the Kingdom of the Netherlands, maintains a strong and evolving relationship with the Dutch government. Communication has increased, marked by the 2023 Memorandum of Understanding, which grants Aruba access to Dutch financial resources like the SDE++ and NEI funds and facilitates the sharing of knowledge on renewable energy technologies [202]. However, historical tensions between the two countries continue to influence their interactions.

International Subsidy Agencies

Given the renewable and emergent characteristics of OTEC projects, leveraging international subsidies, such as the Horizon Europe fund offered by the European Union, could prove viable for funding development. These international subsidy agencies may play a critical role in securing the substantial investment capital required for the successful implementation of OTEC technologies.

Society

Environmental NGOs

Local NGOs in Aruba, often formed by citizens, focus on protecting the island's flora and fauna, ranging from specific species like sea turtles and birds to broader marine ecosystems and national parks. The largest, the ACF, manages and expands protected nature areas. Environmental NGOs have previously raised concerns about renewable energy projects, such as wind turbines, leading to the discontinuation of the Urirama wind farm project [203, 204]. Effective communication with these groups is crucial for OTEC implementation to avoid conflicts, as past projects have faced friction due to insufficient dialogue [205].

Sustainable Development (SD) and Networking Organisations

These internationally based organisations support the implementation of RETs and the energy transition through donations, advocacy and knowledge-sharing platforms. Specific organisations like the Ocean Thermal Energy Association focus on OTEC, while others like IRENA's SIDS Lighthouse Initiative and the Rocky Mountain Institute's Island Energy Program concentrate on SIDS. They have significantly contributed to RET projects in Aruba by providing funding and expertise, particularly in solar farm development and their knowledge of RET implementation in SIDS could be valuable for OTEC deployment in Aruba [177].

Media

Media coverage significantly influences public perception of climate change, sustainability, energy transition and renewable energies. By shaping the narrative, the media can create a positive or negative attitude towards OTEC, which in turn can motivate authorities, attract researchers and persuade citizens.

End Consumer

The main electricity consumers in Aruba are households, the tourism sector, industry and commercial businesses [137]. As these consumers are primarily concerned with electricity prices, it is crucial to consider the impact of OTEC on the total electricity system cost when assessing its feasibility.

Knowledge Institutions

Universities

Universities can aid OTEC's development through research and in some case pilot projects and testing such as at the Saga University in Japan [206]. Additionally, policy research can aid in influencing the regulatory framework for OTEC, providing data and expertise that can help shape policies promoting RETs such as OTEC, as highlighted by Salz (2018) [139].

Research Institutes

Research institutes are dedicated to conducting research in specific fields or disciplines and can be standalone entities or part of larger organisations such as universities, corporations or governmental bodies. They focus on advancing knowledge through scientific studies. Research institutes dedicated to ocean technologies such as OTEC can be found around the world such as the Indian National Institute of Ocean Technology [207] and are an important source of knowledge for the development of OTEC's technologies.

7.1.2. Overview Stakeholder Network

In this section the stakeholder network composition is described: firstly, the network of the proposed stakeholders with strong ties involved in the implementation of OTEC. This is followed by adding additional stakeholders with moderate ties. Lastly, the stakeholders with weak ties are included.

Stakeholder network: strong ties

The strong ties are largely formed by the stakeholders which will be part of the new, to be formed, energy and value chains. An overview of the stakeholder network with strong ties is presented in Figure 7.4. The yellow lines represent the energy value chain and the green lines the monetary value chain.

The OTEC project developer (IPP) is central in the implementation of OTEC. This stakeholder oversees the development, construction and maintenance of the OTEC plant and can hire Technology Advisers to design and/or build parts of the system such as the cold-water pipes, heat exchangers, pumps, compressors and turbine, etc. and provide general consultancy advice on OTEC's development.

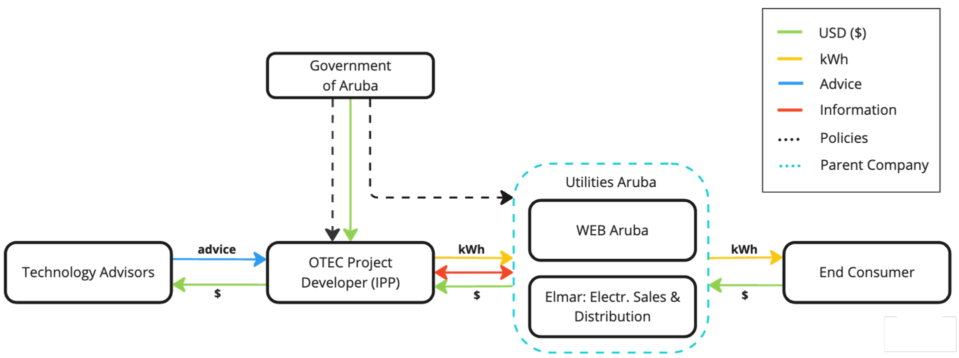


Figure 7.4: Stakeholder network with strong ties.

The Project Developer (IPP) would have close ties to the electricity companies WEB Aruba and Elmar as well as their holding company Utilities Aruba. There are different possible collaboration approaches. One such approach can be seen with NuCapital from Vader Piet Farm. Here NuCapital operates as an IPP. It developed the project and currently operates the wind farm, selling the generated electricity to WEB through a power purchase agreement [83]. Another approach is that an independent developer designs and builds the plant and delivers it to WEB to operate, as is the case with the utility scale Sunrise Solar Park [177]. In both instances, electricity generated must thereafter be sold to Elmar, the only entity legally authorised to manage the country's power infrastructure and distribute electricity to end consumers. Recently, Elmar has been granted additional concessions by the Aruban government to produce electricity as well [208]. Consequently, both WEB and Elmar now qualify as potential buyers of electricity from IPPs. Utilities Aruba plays a pivotal role in ensuring strategic and operational coordination between WEB and Elmar, making it a key stakeholder in the negotiation processes during the development of an OTEC project.

The Government of Aruba plays an important role in the implementation of OTEC in Aruba on multiple fronts. Firstly, the government is responsible for issuing permits to build facilities on- and offshore and ensuring compliance with regulatory standards. The allocation of permits is handled by the DOW. In addition, the quality of the power connection to the grid is the responsibility of the DTI which falls under the same ministry as the DOW.
Secondly, the government has a strong influence on the management of the state-owned holding company Utilities Aruba and by extension its subsidiaries WEB and Elmar. As a result, governmental policy and vision of the future of renewable energies on the island strongly impacts the directions taken by these companies.
Thirdly, the government has substantial influence through the implementation of policies that would create favourable conditions for OTEC and advance its implementation in Aruba.
Lastly, the government could provide grants or subsidies to the IPP for the development of an OTEC plant. Due to the large Capex required, the Aruban government's contribution would probably be limited, but it would send a powerful signal to larger international governmental bodies and/or subsidy agencies which could provide larger sums of capital.

Stakeholder network: moderate ties

Further ties that were identified are included in Figure 7.5; as an extension of the network with strong ties in Figure 7.4. The additional stakeholders are drawn in normal thickness, to stand apart from the stakeholders with strong ties in bold.

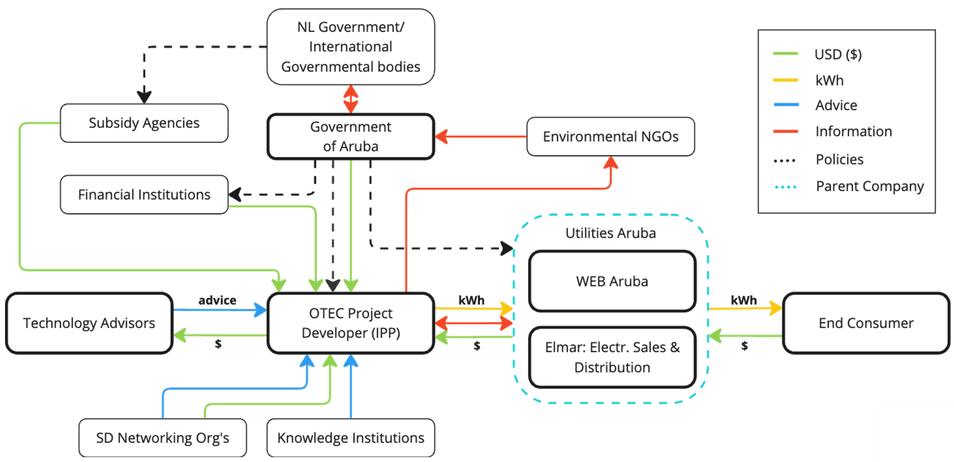


Figure 7.5: Stakeholder network with strong and moderate ties.

Subsidy agencies and financial institutions play important roles in providing funding for the project via subsidies and loans, respectively. The Government of Aruba can help mobilise these stakeholders through the enactment of supportive policies and by leveraging its connections with international governmental bodies, including the Dutch government, the European Union and the United States.

Sustainable Development (SD) networking organisations and knowledge institutions play an important advisory role by sharing theoretical and practical knowledge with the project developer. Knowledge institutions possess advanced technical expertise in OTEC, while SD networking organisations contribute valuable insights through their practical renewable energy project experience, network of experts in varying technologies including OTEC, understanding of SIDS and financial networking capabilities to secure funding. Although SD networking organisations occasionally have the capacity to provide capital assistance, this is often not the case.

Environmental NGOs have historically been active in voicing their opinion with respect to the development of renewable energy projects in Aruba through communication with the Aruban government. This involvement was particularly evident in the case of the Urirama Wind Park, where significant opposition from NGOs resulted in the project being indefinitely postponed [203]. Therefore, effective communication between the project developer and NGOs is critical for garnering public support and minimising opposition.

Stakeholder Network: weak ties

The final stakeholder overview is included in Figure 7.6; as an extension of the network with weak ties. In this figure only information (red) ties are added.

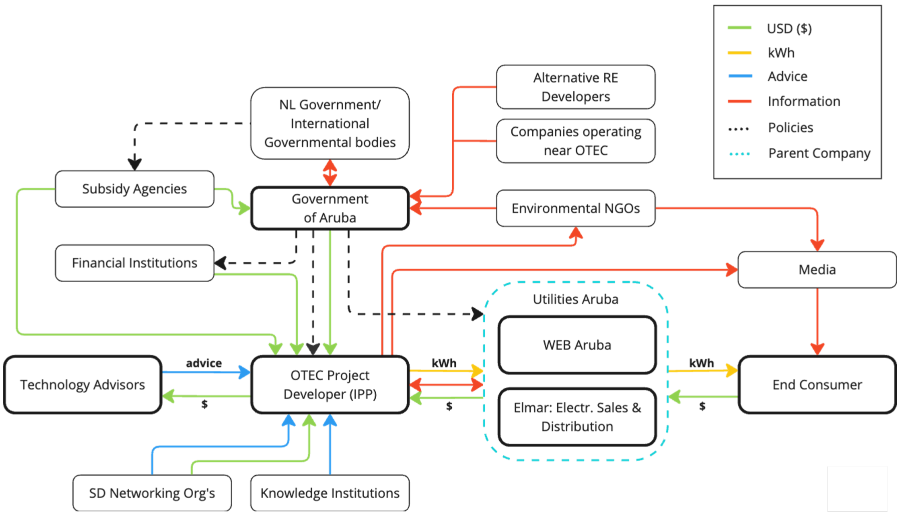


Figure 7.6: Stakeholder network with all ties included.

The media influences public opinion of the project through positive or negative coverage. Obtaining information from multiple sources including the OTEC project developer and environmental NGOs, it acts as distribution network to the end consumers and the general public. This attention can act favourably to attract researchers, motivate the government and persuade inhabitants, thereby creating more favourable conditions for project success. However, it can also hinder the project by echoing concerns from for example environmental NGOs.

Alternative *renewable energy* (RE) developers exert influence on governmental policies through strategic lobbying efforts. Their primary objective is to maximise their share within the electricity market mix. This can both help (e.g. to improve RE developments versus fossil fuels) and hinder OTEC (e.g. by stimulating only one specific RE technology).

Companies operating in proximity to OTEC facilities actively engage with the Aruban government to safeguard their interests. Such interactions may potentially conflict with the objectives of the OTEC project developer. Therefore, vigilance is warranted to manage and mitigate any arising conflicts effectively.

7.1.3. Stakeholder Analysis Conclusion

Considering the different stakeholders in Aruba, several have been identified as pivotal in the implementation of OTEC. These stakeholders are characterised by their significant roles and strong interconnections with other entities within the network. Central in the stakeholder network is the OTEC project developer, which could be an IPP or one of Aruba's state-owned electricity companies, WEB or Elmar. If an IPP serves as the project developer, it will need to establish strong connections with WEB, primarily responsible for electricity generation, and Elmar, which manages the distribution and sale of electricity on the island. The local government of Aruba also emerges as a highly influential stakeholder, with the capability to shape policies and control over both state owned electricity companies, WEB and Elmar. Additionally, given the island's compact nature and governance structure, individuals within the government wield considerable influence over its actions. Furthermore, technical advisors, such as Makai Engineering, are vital in providing the necessary technical and practical expertise for OTEC's deployment in Aruba. These advisors would collaborate closely with the project developer in the engineering and construction of the OTEC facility, emphasising their pivotal role in the network.

7.2. PESTEL Analysis

In this section the results of the PESTEL analysis are presented. The results are presented per category (P)olitical, (E)conomic, (S)ocial, (T)echnical, (E)conomic and (L)egal and the factors are further divided into Drivers and Barriers.

7.2.1. Political

Drivers

Aruba demonstrates exceptional political stability, a critical factor for the success of long-term projects. Notably, it ranked as the most politically stable country in the Caribbean, achieving a score of +1.47 on the World Bank Group's Political Stability Index (ranging from -2.5 to +2.5) in 2022 [18]. This level of stability is crucial for capital-intensive projects like OTEC, as it assures a secure political environment for its development and operation.

Barriers

The renewable transition in Aruba is organisationally complex, as the entities responsible for electricity generation and distribution (WEB and Elmar) operate independently under their parent company Utilities Aruba [110]. Additionally, according to Croes [83] the vertically integrated power structure of the energy companies contributes to bureaucracy and red tape, which creates a barrier for change in the business structure necessary for the effective integration of more renewable energy technologies.

In Aruba, the price of electricity significantly impacts voter behaviour during government elections, thereby providing a strong incentive for governing parties to reduce these rates. This creates a political barrier to the implementation of OTEC if it fails to offer competitive pricing relative to the local electricity rates, in which case it will be difficult to garner political support for the project.

The energy sector constitutes one of the government's largest sources of revenue. Consequently, if an IPP wishes to implement OTEC in Aruba there is a cautious approach towards permitting them to generate electricity, with a specific focus on ensuring that these activities do not lead to a reduction in governmental income. This cautious stance presents a barrier, complicating market entry for IPPs and limiting their potential profitability, as they must ensure that their operations do not adversely affect government revenue.

The government of Aruba could be eligible to access specific funding opportunities from Dutch and EU sources, such as the SDE++ [17] and Horizon EU scheme [209]. However, there is a shortage of human resources and no government body dedicated to facilitating access to these funds. This hampers the government's ability to prepare the documentation required to apply for and secure these funds. This barrier impedes the utilisation of this political aid, limiting the potential benefits that could be derived from such financial support. In the case of an OTEC project, these resources would most likely need to be facilitated by an external party. Previously, TNO played a role in facilitating this capacity, although it has not done so recently.

7.2.2. Economic

Drivers

Aruba has a noteworthy *Gross Domestic Product* (GDP) per capita of 33,300 USD per year, ranking as the fourth highest in the Caribbean [210]. This metric serves as an indicator of Aruba's economic stability and suggests a lower risk for investors. The economic stability is good for the development of new energy projects, providing a secure investment environment. Furthermore, this level of GDP per capita suggests a higher educational attainment, which could supply skilled local labour essential for the development of such projects.

Barriers

Although electricity prices are high in Aruba (with average residential rates of 0.21 USD per kWh [191] and commercial rates even higher) which could facilitate higher LCOEs and therefore renewable energy initiatives, electricity pricing during the sustainable energy transition must remain affordable to all (Croes, 2022) [83]. Current modelling in Section 6 indicates that achieving a 100% renewable energy system by 2050 would still incur higher costs compared to fossil fuels. This forms a barrier as either the end consumer prices will have to be raised or the (government) income from electricity sales will have to be lowered. The potential of fossil fuel price increases is however not taken into account.

Due to Aruba's favourable economic standing it is no longer eligible for development funding or grants, such as the *Green Climate Fund* (GCF). Additionally, as Aruba is a part of the Kingdom of the Netherlands it falls in a "grey area" when applying for regional development funds such as the *Inter-American Development Bank* (IDB), as it is not a member state of the Organisation of American States [211, 212]. This forms a barrier for obtaining financial resources that could greatly aid the implementation of OTEC in Aruba.

The COVID-19 pandemic had a severe impact on Aruba, notably due to the nation's heavy reliance on tourism and global imports [213]. The downturn in tourism and import activities during the pandemic led to a significant contraction of the economy, with GDP experiencing a 23% decrease. Although the country's economy has rebounded to pre-pandemic levels [214], it may still be early to pursue OTEC projects in the near future, given the perceived risk currently still associated with the technology.

7.2.3. Social

Drivers

OTEC provides socially equitable electricity, as it ensures universal access to its generated electricity through the grid. This compares favourably to other RETs such as rooftop PV and Electric Vehicles which many cannot afford in Aruba [215], as everyone pays for the infrastructure investments necessary to facilitate these technologies but not everyone benefits from the advantages (Croes, 2022) [83]. In comparison the electricity generated by OTEC would be accessible to everyone and the costs and advantages distributed equally.

Previous renewable technology projects in Aruba have encountered resistance exemplified by the '*Not In My Backyard*' (NIMB) phenomenon [83]. Given that OTEC facilities would be situated offshore, distant from residential areas, this positioning offers a distinct advantage. It allows for the provision of renewable energy while avoiding the proximity to homes that typically fuels local opposition.

Barriers

Local NGOs, dedicated to the conservation of Aruba's natural environment (flora and fauna), have historically expressed resistance to renewable energy projects, particularly the installation of onshore wind turbines [203, 216, 217]. Concerns regarding the potential impact on local bat and bird populations, property values, health risks and socio-religious considerations have led to the cancellation of such projects. It is therefore important to actively engage with the communities and conduct environmental impact assessments before proceeding with the implementation of an OTEC facility.

Older generations in Aruba often view fossil fuels as a historic cornerstone of the nation's economy. The idea is rooted in the early 20th century when oil refining, spurred by discoveries of oil off the coast of Venezuela, catalysed economic growth starting in the 1930s [218]. This industry predominantly sustained the country's economy until the emergence of the tourism sector in the 1960s, though it remained a significant economic contributor even thereafter. While the oil sector has largely diminished today, many among the older generation still consider this period Aruba's 'golden era'. This sentiment persists within the upper levels of management, occasionally posing barriers to the advancement of renewable energy projects. However, younger generations are increasingly advocating for renewable energy projects.

7.2.4. Technology

Drivers

OTEC's ability to provide base-load renewable electricity [12] decreases the need for energy storage technologies, such as BESS, and demand side management, which are necessary to a far larger extent for a fully renewable energy system with non-dispatchable technologies such as wind and solar PV. Additionally, Aruba has one of the most reliable electricity supplies in the Caribbean, which Is key for the tourism industry [83]. OTEC's ability to provide a renewable baseload would further improve its electricity supply's resilience.

Barriers

A significant barrier for OTEC is the higher initial capital investment necessary compared to traditional fossil fuel technologies and other renewable options such as wind turbines and solar panels, when storage isn't considered. Due to the high capital investment necessary to finance OTEC and limited OTEC facilities currently in operation there is a barrier present when obtaining financial backing from traditional financial institutions due to the associated risk [219]. Due to the large investment required, local banks and financial institutions are likely to find it challenging to provide sufficient funding for OTEC projects. Consequently, securing adequate financing will necessitate seeking financial support from international financial institutions such as commercial banks or large international organisations, such as Shell or NuCapital. Alternatively, financial institutions such as development banks or climate funds (such as the Climate Investment Fund and Energy Transition Accelerator Financing Platform) could be approached to provide the necessary funding.

Floating OTEC exhibits economy of scale. Consequently, the smaller-scale plants are uneconomic due to the relatively high cost of the mooring cables and sub marine transmission cables to shore. This poses a barrier, as the initial smaller plants are generally not financially viable without some form of financial support or high electricity prices, forming a barrier to the further development of the technology.

The development of large-scale BESS in recent years has been steep. With significant reduction in costs and increase in deployment, mainly in China and the USA [220]. As the implementation of wind and/or solar PV in combination with BESS would have the same advantages as OTEC, moving towards a 100% renewable energy system, it could be considered a competing technology and could become a barrier to OTEC's deployment if those technologies would become more economically attractive. For this, one needs to consider that the scale of BESS would need to be very large, compared to a system with OTEC included as it would have to facilitate the seasonal swings of wind and solar PV resources. Additionally, Aruba would remain reliant on non-dispatchable energy sources in such a system.

7.2.5. Environmental

Drivers

Aruba's geographic location is ideal for the implementation of OTEC. Situated close to the equator between 20 and -20 degree's latitude it has an average sea surface temperature of 28°C [28]. Additionally, the fluctuation of the surface temperature is minimal leading to a relatively constant electricity output [13].

Aruba, being an SIDS, is highly exposed to the effect of climate change. With effects such as increased number of hurricanes and other extreme weather events, sea level rise, high temperatures, coastal erosion and ocean acidification [221]. As such there is an inherent environmental driver to facilitate renewable technologies such as OTEC.

Aruba is located at the bottom of the Caribbean hurricane belt. As a result, historic data indicates that a severe storm resulting in considerable damage on and around the island is rare, especially compared to other islands in the Caribbean. This only occurs approximately once every 100 years, with tropical storms passing at about 150km from Aruba's coastline every four years [222]. This substantially decreases the risk of damage on offshore technology such as OTEC in Aruba compared to other Caribbean islands, facilitating a favourable build environment.

Floating OTEC systems necessitate minimal onshore infrastructure since most of the facility is situated offshore. It requires only a limited area onshore to accommodate the onshoring of the deep-sea cable to connect to a substation. As land on the island is very limited [223] in addition to the concerns for wildlife on the island, there is a substantial environmental interest in minimising onshore construction.

Barriers
OTEC's impact on the environment is currently understudied with most of the studies based on theoretical revisions and modelling exercises. As a result, the effect on the environment cannot be known for certain which may act as a barrier for its implementation due to environmental concerns. However, field and laboratory experiments and observations are beginning to accumulate [16, 224] and research so far has shown that the effects would be mitigable [225]. In addition to this, the amount of biodiversity offshore in Aruba at the discharge depth is limited. Nevertheless, thorough environmental assessment studies must be conducted which could act as a barrier as was the case in the Bahamas in 2011 [92].

Aruba has relatively shallow (<1000m) waters close to shore. With the first access to 1000m deep ocean approximately 15km offshore [100]. Sub-sea cables will be required to connect the floating OTEC plant to shore. This technology is mature and available but provides an increased cost and subsequent barrier [226]. Also, mooring cables will need to be relatively long and therefore be expensive with the facility not being able to profit from a steeply sloping seabed. This would suggest Aruba would not be a good place for testing and developing the smaller scale OTEC plants and would be more suitable for the larger scale (40-50 MW) plants, where the larger scale would reduce the unit costs.

7.2.6. Legal

Drivers
Ursell Arends, Aruba's Minister of Transport, Integrity, Nature and Elderly Affairs has proposed a constitutional amendment aimed at recognising the inherent rights of nature, positioning it to become the second country globally to adopt such a measure. This amendment would mandate the government to "take preventative measures to protect against the negative consequences of climate change" [227]. Such a constitutional mandate could significantly enhance the integration of renewable energy technologies, including OTEC, into Aruba's energy portfolio, providing a robust legal foundation for increasing the share of renewable energy.

Barriers
Aruba has constructed an energy policy in which the goal to reach a renewable energy generation of 50% is expressed [137]. However, this policy appears to favour increased energy efficiency and the introduction of less pollutant fossil fuels such as LNG instead of HFO to the construction of new renewable energy technologies. Consequently, the regulatory framework for renewable energy projects, such as OTEC, in Aruba is currently underdeveloped. This absence of clear and, in an ideal case, targeted regulations may present barriers when integrating such a novel technology within the framework of established policies.

It was recently announced that the Aruban government, in collaboration with Utilities Aruba, has entered a 20-year 'take-or-pay' contract with Eagle LNG, committing to purchase approximately 50% of the country's electricity needs from the provider [110]. Under the terms of this agreement, for the next two decades, Aruba is obligated to either utilise or compensate for 50% of its electricity demand from Eagle LNG. This contractual obligation presents a significant barrier to the implementation of OTEC in the short term, as it renders the adoption of more than 50% renewable energy economically unfavourable; the country would still be required to pay for the LNG regardless of its actual energy consumption [228].

Currently, there are no existing policies that actively promote or support the implementation of OTEC in Aruba [137]. Consequently, this absence of targeted regulations may present barriers when integrating such a novel technology within the framework of established policies.

Legislation governing electricity generation is not entirely clear in Aruba, unlike for example Bonaire, where the legislation governing electricity generation is well-defined, Aruba lacks clarity in its legal provisions for energy production. Further compounding this issue, the absence of an independent regulatory body to oversee electricity generation contributes to an ambiguous and potentially less appealing investment climate.

7.2.7. PESTEL Conclusions

The findings from the PESTEL analysis, incorporating expert consultations, reveals a complex landscape for the implementation of OTEC in Aruba, characterised by both facilitating drivers and barriers across political, economic, social, technological, environmental and legal dimensions.

Political factors: Aruba's exceptional political stability is conducive for long-term projects like OTEC. However, challenges such as a complex organisational structure within the energy sector and significant political pressure to maintain and lower electricity prices create barriers to OTEC's implementation.

Economic factors: while Aruba's stable economy provides a strong foundation for investment, the country's exclusion from certain international development funds due to its economic status, coupled with a competitive energy market favouring less costly energy sources over OTEC, poses economic barriers.

Social factors: resistance from local NGOs, concerned with environmental impacts on native flora and fauna, underscores the necessity for comprehensive engagement and environmental assessments to garner local support and mitigate social opposition.

Technological factors: technological advancements in OTEC components signal potential for future development. However, the current limitation in the scale of feasible OTEC plants and the high initial capital investments required present significant technological and financial barriers.

Environmental factors: Aruba's geographic and climatic conditions are highly favourable for OTEC, offering consistent energy output. Nonetheless, logistical challenges related to the island's bathymetry and the costs associated with offshore infrastructure development may limit the viability of smaller-scale projects and favour larger installations.

Legal factors: the existing energy policy, while aiming for a significant share of renewable energy, inadequately supports the integration of innovative technologies like OTEC, with a legal framework that needs further development to facilitate such advanced renewable energy projects and current plans for LNG implementation forming barriers for the renewable energy transition in the short term.

Moving forward, Aruba must address these multifaceted barriers while leveraging its environmental advantages and political stability to foster a supportive framework for OTEC. This will involve revising legal structures, enhancing financial incentives and improving technological capacities to accommodate and effectively implement OTEC solutions, potentially transforming its energy landscape and contributing to its sustainability goals.

7.3. Key Stakeholders for Implementation

Here the ability of each stakeholder to either help or hinder OTEC's implementation in Aruba is presented in Figure 7.7 and elaborated upon. The key stakeholders have been made bold. The underlying scores are presented in Appendix E.

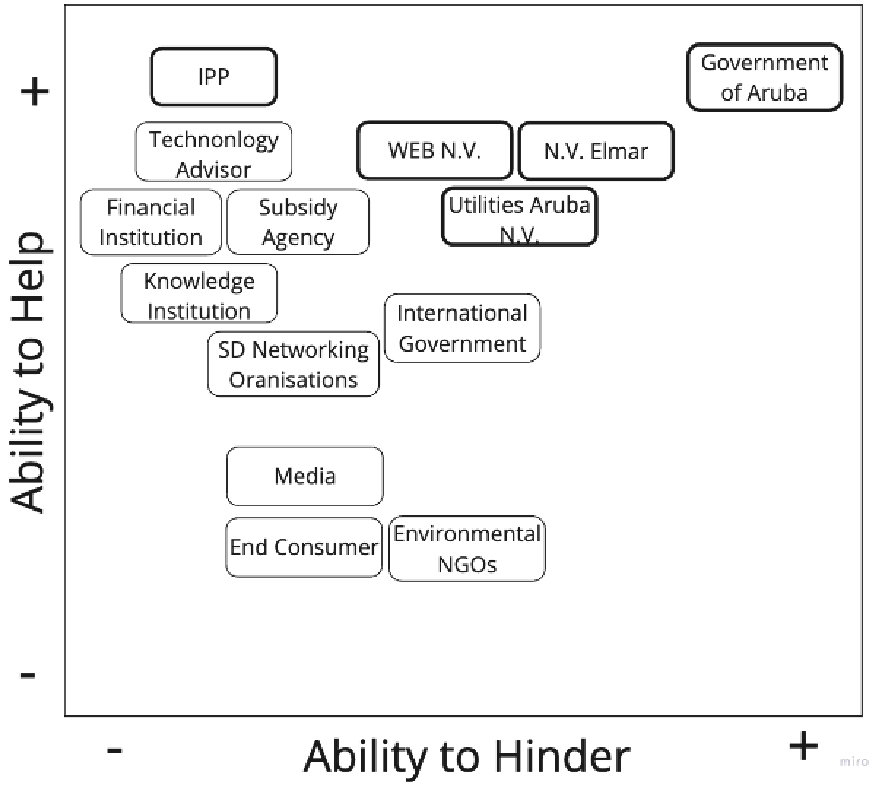


Figure 7.7: Matrix of stakeholder ability to help and hinder OTEC's implementation in Aruba.

The Government of Aruba is identified as the most influential stakeholder in the context of OTEC's implementation. Its influence is primarily exerted through the management of Utilities Aruba and its subsidiaries, WEB and Elmar, as well as through its legislative power to enact policies that could either facilitate or obstruct OTEC deployment. Additionally, its authority to approve or deny development and construction permits influences OTEC's implementation greatly. Ideally, the government should not wield decisive influence over the adoption of specific technologies. However, in practice, the interconnected nature of Aruba's societal and political structures, along with the substantial sway of its political leaders, ensures that the government plays a pivotal role in the practical implementation of such technologies on the island.

The IPP holds a pivotal position within the stakeholder network to facilitate the implementation of OTEC. Serving as the primary driver for the implementation of OTEC, the IPP effectively connects all relevant stakeholders, orchestrating their interactions to streamline the implementation process.

Utilities Aruba and its subsidiaries, Elmar and WEB, each possess the potential to impede the implementation of new projects. This is especially the case for Elmar, which, as the sole entity granted concessions to sell electricity to end consumers, and now also authorised to generate electricity, holds significant influence. However, these entities also play an important role in helping OTEC's implementation by entering into agreements with the IPP to purchase electricity, thereby supporting the integration of new energy projects into the existing infrastructure.

Lastly, environmental NGOs have historically demonstrated a capacity to obstruct the implementation of renewable energy projects, underscoring the importance of considering their influence seriously when deploying new technologies. Nevertheless, the recent approval of the new LNG terminal illustrates that, when the government is committed to a project, it can proceed to implementation despite opposition. This indicates that government resolve plays a critical role in OTEC's implementation [229, 230].

7.4. Roadmap to OTEC's implementation in Aruba by 2050

The long-term deployment of renewable energy technologies like OTEC is inherently complex and has an inherent level of uncertainty. A roadmap is used to outline a possible strategy for implementing OTEC in Aruba, providing a visual guide to navigate these complexities. As stated by Blackwell et al. [143], roadmaps are notably versatile tools, that have been adapted to support various goals, including the advancement of innovation, strategic planning and policy formulation. This flexibility has contributed to their broad application, yielding a variety of methodological approaches across different fields.

Based on roadmaps described in Phaal et al. [144] a roadmap is developed, with as goal to provide a high level view of the necessary steps that could be taken to implement OTEC in Aruba in the future. OTEC's current global development and Aruba's local stakeholders and institutional direction, discussed in Sections 5.2.1, 7.1.1, 7.2 and 7.3 respectively, are taken into consideration.

To develop the roadmap the following steps are undertaken:

1. Formulate the current state of OTEC in Aruba and define the objective.
2. Develop a timeline for the global technological development necessary for OTEC in Aruba.
3. Develop a roadmap for implementing OTEC in Aruba.

7.4.1. The current state of OTEC in Aruba and strategic objective

Based on the power system model and PESTEL analysis, supported by expert consultations, it is determined that a stand-alone 1-10 MW OTEC plant in Aruba is not cost-efficient without subsidies or other forms of financial support. Furthermore, expert consultations indicate that Aruba is not the ideal candidate for a small-scale pilot plant in the region, as Curaçao (which is also located in the Lesser Antilles) has access to deep seawater closer to shore, approximately 3 km compared to 15 km in Aruba [98], and possesses infrastructure facilities such as a dry dock, which would facilitate OTEC implementation and maintenance. In contrast, Aruba lacks such facilities. However, OTEC plants with capacities greater than 35 MW are found to be cost-competitive, with power system model analysis suggesting that multiple large-scale OTEC plants between 75-100 MW, with a combined capacity of 175 MW or larger, would be the most cost-effective option for a renewable energy-based electricity system in Aruba by 2050 across multiple scenarios.

Furthermore, it is found that the government of Aruba recently entered into a 20-year ”take or pay” agreement with Eagle LNG [110]. This contract complicates the economic feasibility of achieving more than 50% renewable energy integration until 2046 or 2047, as payments for the LNG supply will still be required regardless of usage. Although renegotiation of the contract or employing financial mechanisms, such as the Just Energy Transition Partnership program implemented in Indonesia and South Africa [231], could be potential strategies, this analysis assumes that the contract will be upheld for its full duration. Consequently, this agreement is likely to constrain Aruba's transition to a fully renewable energy system until the contract expires. As OTEC is found to be economically viable in Aruba's energy system from a 50% renewable share in the electricity mix and higher, it is noted that the LNG contract could pose a barrier to OTEC's implementation until it expires.

As construction of a small scale pilot plant is not found to be cost competitive, with expert consultation indicating that Curaçao is the more likely candidate for such a pilot facility in the region, Aruba appears to be well suited for the implementation of OTEC later on in its development cycle. Additionally, this fits with the timing of the new LNG contract. As such the target date for OTEC's implementation is set to 2050.

Taking the findings described above the objective for the implementation of OTEC in Aruba is taken to be the following:

Implement a commercial scale (40 MW+) OTEC plant to be operational in Aruba by 2050.

7.4.2. Timeline for OTEC's technological development

An OTEC plant with a capacity of approximately 40 MW would surpass plants built to date. It is therefore important from an Aruban perspective to monitor the ongoing advancements in OTEC technology. This includes observing the progress in essential components such as the cold-water pipes and heat exchangers, as well as monitoring the construction of anticipated plants such as Global OTEC's 1.5 MW plant in São Tomé [7] and the US Army's potential plans for an OTEC facility in Kwajalein Atoll [232]. The subsequent critical global development steps and milestones are described below and presented graphically in Figure 7.8.

1. Construction and operation of a 1 to 10MW gross plant.
2. Proof of Concept (*PoC*) for technical components required for a 10+MW gross plant.
3. Design, build and operate a 10-40MW gross plant.
4. PoC for technical components required for a 40+MW gross plant.
5. Design, build and operate a 40+MW gross plant.

It is difficult to give an exact estimate for the time required for each of these steps. Therefore, a range is given as a rough indication of when each step will take place based on offshore wind farm projects from Iberdrola, a global leading energy producer [233] :

1. Build 1-10MW plant: 7-11 years (ready by: 2031-2035)
2. PoC 10+MW plant: 1-3 years (ready by: 2032-2038)
3. Build 10+MW plant: 7-11 years (ready by: 2039-2049)
4. PoC 40+MW plant: 1-3 years (ready by: 2040-2052)
5. Build 40+MW plant: 7-11 years (ready by: 2047-2063)

An overview of this timeline is given graphically in figure 7.8.

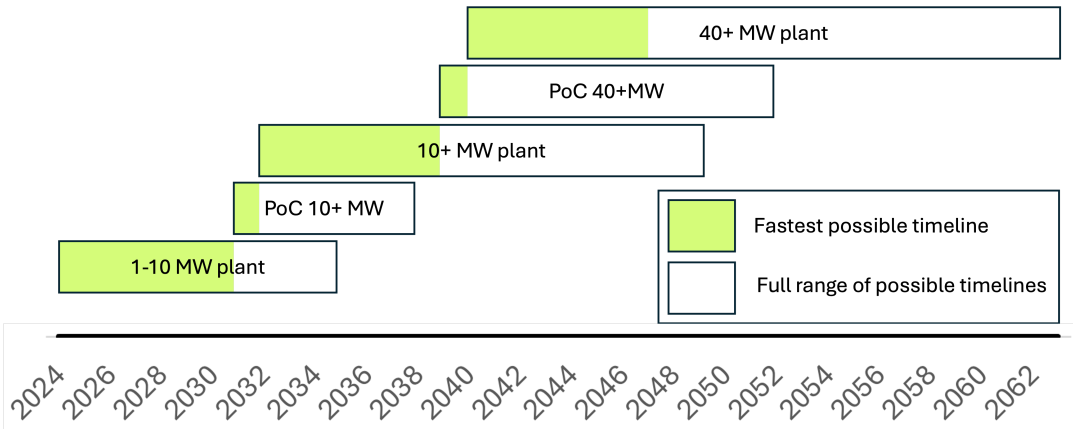


Figure 7.8: Global OTEC development timeline.

7.4.3. Roadmap for implementation of OTEC in Aruba

The implementation of OTEC in Aruba is divided into three phases subsequently named: the (1) monitoring, (2) decisions and structuring, and (3) development phase. Each is described below with an overview presented in Figure 7.9.

Monitoring phase

The political willingness by the government to move to a 100% RE system will be critical to make the implementation of OTEC possible. With the recently signed 20-year LNG import deal, a move to a large-scale OTEC plant is economically more difficult until after 2046/47. This would however fit well with the roadmap shown in Figure 7.9. The choice to seriously consider OTEC as a viable technology in the future must be taken as soon as possible however, to set in motion the phases necessary to achieve OTEC's implementation.

As outlined in Section 7.4.2, during the initial period from 2024 to 2032/38 it will be critical to monitor the global progress of the technological development of larger OTEC plants. A consensus must be reached who in Aruba is responsible for this monitoring. This could either be done by the Government of Aruba (e.g. by the policy advisor Sustainability in the Ministry of Economic Affairs together with someone from the Ministry of Energy) or by Utilities Aruba, possibly through its subsidiaries WEB or Elmar. The monitoring could involve assigning an individual the responsibility of attending relevant conferences and preparing annual reports on advancements in renewable energy technologies, including OTEC. During the successful construction and operational deployment of a 10+ MW OTEC plant globally, the project can transition to the decision and structuring phase.

Decision and structuring phase

In this phase Aruba can prepare itself by (headings in bold below refer to Figure 7.9):

- **Evaluating Economics (Econs)**: reviewing the economic feasibility of OTEC as part of Aruba's total energy system. Confirm that OTEC is still part of the lowest cost 100% RET electricity system. As part of this the following actions will be required:
  - a feasibility analysis of the best locations for an OTEC facility
  - grid studies analysing the effect of OTEC on the grid
  - evaluation of Aruba's ability to apply for international/Dutch funding such as Horizon Europe, SDE++, NEI
  - work out scenarios through power system modelling
- **IPP Engagement (IPP)**: starting active engagement with potential IPPs and technology advisers
- **Decision Milestone (D)**: deciding whether to be an early adopter of a 40+ MW plant and to set in motion the project to construct a 40+ MW OTEC plant.

These evaluating economics, IPP engagement and the decision milestone steps are taken to last 2-3 years in the period 2036/39.

- **Landscape**: designing the OTEC landscape: identify who will be the players and what their role is (will WEB own, develop and operate the OTEC plant or will IPPs be encouraged to play a role), how will they best interact and what incentives will be provided through government policies. This phase is assumed to span 1 to 3 years, occurring within the period from 2039 to 2042. In parallel to this, broader changes to the energy sector organisation could be made as per suggestions from the expert consultations, e.g. the introduction of an independent regulator and hiring of a specialist in international processes such as subsidy requests.

The government of Aruba through the Minister of Energy and Minister of Economy will be two of the key decision makers whether and when to move to the next (Development) phase and to what extent incentives will be offered to the project developer. Utilities Aruba and WEB will most likely be involved and may even lead the analysis, in particular if WEB will become the main project developer. For Aruba it may be beneficial to get one or two potential IPPs and/or technology advisers interested and involved in this stage, so that the landscape and policy incentives can be set up in a way that will attract sufficient interested players for the next, development stage. For IPPs such an early involvement may be of interested, as they can develop an early awareness of local circumstances and it provides them an opportunity to influence the business model they may potentially operate in. Technology advisers will most likely be eager to be involved but may already expect to be paid for their services during this stage.

The following regulatory and policy incentives during this phase would be beneficial to OTEC's development:

- Set a clear target (close to 100%) for RE in Aruba by 2050.
- Include Take or Pay clauses in contracts for RET projects (like the one for LNG), which will result in an effective utilisation factor of 90-95% for OTEC.
- Provide fiscal incentives such as no import duties for RET's construction and income tax breaks.
- Provide subsidies and at least minimum red tape for international subsidies.

Development stage
Once the decision has been made to develop and construct OTEC in Aruba and the structure of the OTEC landscape is clear, the actual project development stage can begin. The following steps are described, based on offshore wind projects [233]:

- **Scope**: deciding aspects such as the capacity of the OTEC plant (40-100 MW), at what location to build the plant, the electricity cable routing (on and offshore) as well as its landfall location.
- **Permits**: granting of permits, such as the location of the plant and the routing of the electricity cable.
- **Financing**: arranging financing and subsidies, including Final Investment Decision (FID) by the project developer (WEB and/or IPP).
- **Design**: detailed designing of the plant.
- **Build**: building the plant.

This is assumed to take approximately 7-11 years in the period 2042-2052. Delays due to e.g. permitting issues and local protests are always possible and will be one of the risks that will need to be managed.

In this phase, the project developer will take the lead (whether this is WEB or an IPP). However, the government will have to confirm the scope of the project (e.g. regarding security of supply and impact on the country's budget), grant concessions through the DEHZI, issue the permits through the DOW, potentially provide incentives for subsidy and financing agencies and check that the building of the plant is according to local standards through the DTI.

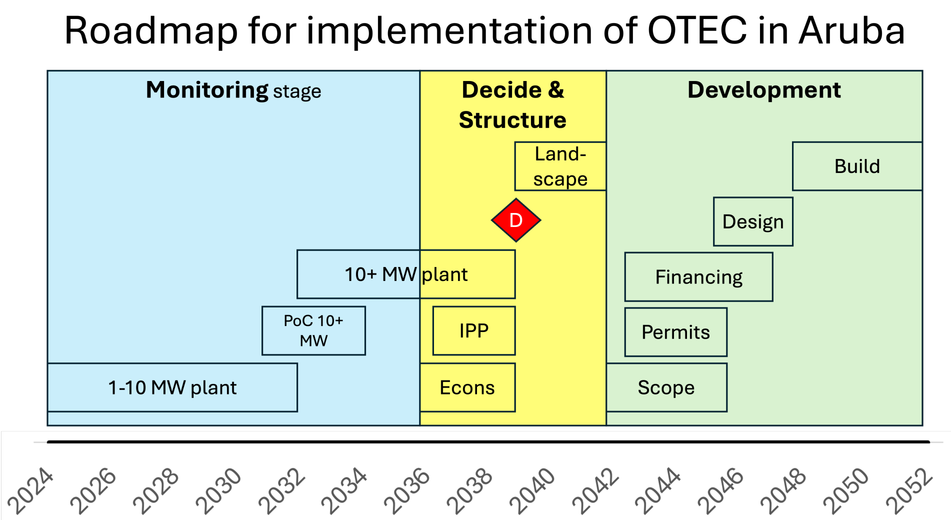


Figure 7.9: Roadmap for implementation of OTEC in Aruba.

7.5. Conclusions

Aruba has a complex network of stakeholders which would need to interact to facilitate the implementation of OTEC in Aruba. The most important identified stakeholder is the Government of Aruba as it holds the most power to help but also to hinder OTEC's implementation. This influence is exerted through legislative actions, the issuance of necessary permits and policy decisions and most importantly the government's influence over the state-owned holding company, Utilities Aruba, which oversees entities such as WEB and Elmar. WEB and Elmar play critical roles in electricity generation and distribution on the island, with WEB owning and operating most of the generation facilities and Elmar holding exclusive concessions to distribute electricity to end consumers. Additionally, it is expected that involving an Independent Power Producer would be beneficial to OTEC's implementation.

It is found that although Aruba displays favourable conditions for OTEC that would drive its implementation such as a demonstrated political and economic stability in the country and good environmental conditions for OTEC, there are certain barriers to take into consideration. The most important ones are the recent LNG “take or pay” deal between the Government of Aruba and Eagle LNG limiting Aruba’s renewable energy share to 50% for the next 20 years, the expected need for an OTEC plant that is larger than what is considered technologically feasible today and the historical resistance from certain environmental NGOs against renewable energy projects. For the successful implementation of OTEC these barriers will have to be overcome.

The implementation of a commercial OTEC plant appears to be feasible in Aruba by early 2050s, taking into account OTEC’s global development and necessary steps by the government of Aruba and commercial parties. Globally this would require the implementation of smaller sized OTEC plants (1-10 MW) to facilitate the knowledge gathering to build commercial stage plants above 10 MW and developing the engineering designs and proof of concept of components for OTEC plants above 40 MW by around 2040. Locally in Aruba the government would initially be advised to monitor the global developments and when the technology has matured (for example between 2036-2042) start undergoing steps to facilitate the implementation of OTEC in Aruba such as feasibility analyses of the best locations, undertaking grid studies, working out different scenarios as is done in this work as well as designing the OTEC landscape (who does what, which policy incentives will be provided). It is advised to also develop active engagement with IPPs who could coordinate the development phase, which would include the detailed design of the plant, acquisition of permits and financing and eventually build and possibly operate the plant. This development phase could then start in the early 2040’s.

8 Discussions

8.1. Current and future state of fossils and renewables in Aruba

Aruba possesses abundant renewable energy resources from a limited set of RET options, namely wind, solar and ocean thermal energy. However, the country currently relies heavily on fossil fuels, with 85% of its electricity generated from HFO and LNG [234]. As Aruba lacks domestic fossil fuel resources, these fuels must be imported, costing the country approximately 100 million USD annually for electricity generation alone. When accounting for all local fossil fuel consumption, Aruba's total expenditure on imports ranges between 140 and 167 million USD per year, which is about 5% of its GDP [235].

Aruba could strive for a higher share of RE, harnessing the renewable energy resources on the island. In the short to medium term, it appears most economically prudent for Aruba to expand its onshore wind and solar capacity to increase the share of renewable energy on the island. These technologies are well-established and have demonstrated economic competitiveness, particularly when their share in the energy generation mix remains moderate, thereby avoiding the need for costly storage solutions. However, in the long term, OTEC emerges as a promising candidate to support Aruba's transition to a fully renewable energy system. The island's limited land availability poses significant constraints on land-based renewable energy technologies. In contrast, OTEC's offshore deployment capability, coupled with its potential to provide a stable base load, could offer a strategic solution for delivering the additional capacity needed to achieve a fully renewable energy system in Aruba. Nevertheless, as it is found that OTEC only becomes economically viable without subsidies at larger scales further global development in the near term is critical, with pilot projects being essential to demonstrate the technology's viability at a commercial scale. Financial aid from the Netherlands and the EU should be taken into consideration when investigating OTEC's economic feasibility further in the future with the ties between Aruba and the Netherlands strengthening [179].

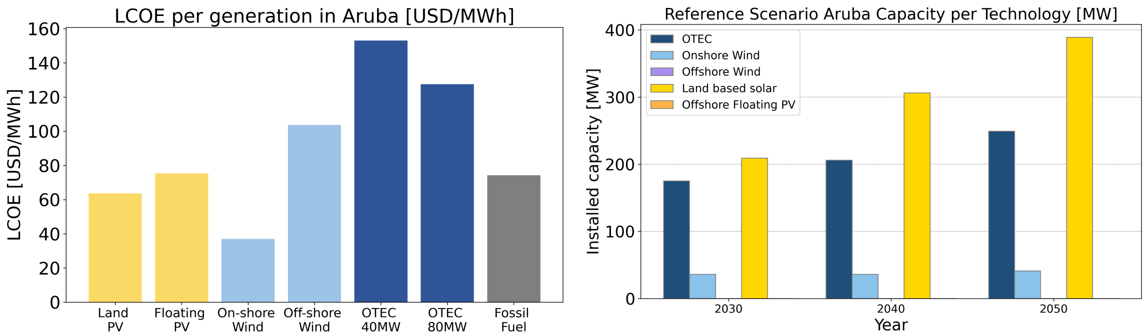
8.2. Impact of dunkelflaute on OTEC's implementation in Aruba

Analysis of historical data from 1980 to 2023 reveals that Aruba experiences systematic fluctuations in wind and solar energy resources. Notably, both wind and solar resources tend to decrease during September to November, which corresponds to a period exhibiting characteristics akin to dunkelflaute, a prolonged period of significantly reduced renewable energy generation. Additionally, periods of diminished wind and solar resources are observed at the beginning of the year; however, these occurrences are more irregular year by year, both in frequency and severity. All in all, wind is at a near standstill for a total 2-3 months a year [110]. The implications of such dunkelflaute for Aruba are that substantial energy storage capacity is required to ensure a fully renewable energy system can consistently meet demand if relying solely on wind and solar energy sources. Due to Aruba's flat and arid environment, PSH is not feasible, necessitating the use of less mature or more costly storage technologies such as BESS or hydrogen storage.

The high costs associated with the required storage technologies, specifically BESS, suggest that integrating base load technologies like OTEC at a commercial scale could become economically competitive. This creates a dynamic where OTEC emerges as the cost-optimal solution in energy system modelling. It is however observed that OTEC at a small scale such as a 10 MW plant does not appear to be economically competitive, even considering the high storage costs, further underscoring the importance of advancing OTEC to a commercial stage.

8.3. Impact of dunkelflaute on the concept of LCOE

The techno-economic analysis in Section 5 reveals that the LCOE for onshore wind is the lowest among the RETs and conventional plants in Aruba, as shown in Figure 8.1a. Moreover, this coincides with the power system modelling results in Section 6, where onshore wind consistently has the lowest LCOE across all reference scenario years, as detailed in Table 6.2. Based on this, it was expected that onshore wind would be heavily deployed in the power system model. However, it is observed that onshore wind is not deployed to its maximum and is deployed less than utility-scale land-based solar PV, despite solar PV having a higher LCOE, as illustrated in Figure 8.1b. Additionally, OTEC, which has a significantly higher LCOE, is implemented with a much larger capacity than onshore wind. This is likely due to the need to address periods of dunkelflaute, where both wind and solar resources are scarce.



(a) LCOE analysis. **(b)** Power system modelling results.

Figure 8.1: Comparison of LCOE analysis and power system modelling results.

This prompts a discussion on the concept of LCOE—a widely used metric for comparing the lifetime costs of electricity generation technologies [236]—when assessing the most cost-efficient technologies from a power system-wide perspective. Although the concept of LCOE is useful it has its limitations. The limitations of the LCOE metric, especially when applied to RETs dependent on intermittent resources such as wind and solar, have been been highlighted in literature, beginning with Joskow (2011) [237] and further explored in more recent studies by Ueckerdt et al. [238], Loth et al. [239] and Matsuo [240]. These works assert that LCOE is useful for comparing the generation costs of conventional power plants with those of RETs, due to the differing cost structures. RETs typically have high fixed costs and negligible variable costs, in contrast to conventional technologies, which have different fixed-to-variable-cost ratios. However, as described by Matsuo [240] its effectiveness is limited as it does not account for ”integration costs”, which are crucial for evaluating the true cost of incorporating RETs into the power system.

Integration costs refer to the additional expenses incurred due to intermittent RE resources, such as wind and solar [240]. These costs partly arise from the location-specific requirements of RETs, which tend to be less flexible than fossil fuel plants. As a result, a more extensive grid infrastructure is necessary to transport electricity from remote sources, such as isolated wind farms, to demand centers in urban areas, leading to increased transmission costs.

More importantly, however, is the issue of timing in electricity generation [239]. While the LCOE reflects the cost of producing electricity, the primary role of power supply in electricity markets is not simply to generate electricity, but to deliver a specified amount to a particular location at a particular time. Since intermittent renewable energy sources are non-dispatchable, meaning they cannot be adjusted to match demand, they warrant additional balancing, storage and grid costs. These integration costs are not accounted for in the LCOE, as illustrated by the comparison between LCOE and electricity system modelling results in Figure 8.1, where the added costs associated with dunkelflaute periods are not reflected in the LCOE calculations.

Ueckerdt et al. [238] address this limitation by introducing the concept of ”System LCOE”, which incorporates ”integration costs” by evaluating the entire power system rather than individual technologies. This approach provides a more comprehensive view of the total costs, including the additional expenses associated with intermittency, such as those that arise as a consequence of periods of dunkelflaute. Incorporating this approach can lead to unexpected results as demonstrated in the power system model, which optimises for minimal total system costs. Applying this approach offers a more comprehensive representation of the economic impact of renewable energy integration, especially at higher RET penetration.

The ”System LCOE” concept introduced by Ueckerdt et al. has been further refined by work such as Reichenberg et al. [241] and Matsuo [240]. However, it has been found that this metric may be too complicated and ”not catchy” enough to be used for non-academic audiences [241]. While LCOE calculations are by no means simple, the intent of this discussion is to emphasise the need for the adoption of a cost measure that incorporates the additional costs of intermittency caused by, for example, periods of dunkelflaute. Such a measure is essential for providing a more comprehensive understanding of the true costs when considering high penetration of renewable energy technologies in power systems. In this work the concept of ”Levelised Cost of the System” (LCoS) has been used, which is similar to the ”System LCOE” concept.

8.4. Implications of dunkelflaute for fully renewable SIDS

SIDS are strategically positioned both geographically and geomorphologically to harness a diverse array of RE resources, including solar, wind and ocean thermal energy. Additionally, certain SIDS possess potential for geothermal energy, hydropower, tidal and wave energy, depending on their specific geological conditions [9]. In regions where geothermal and hydropower resources are accessible, energy systems that integrate solar, wind, geothermal and hydropower are often the most cost-effective options for achieving a fully renewable energy system [56]. The technological maturity of these technologies, coupled with steadily declining costs, renders them a logical and cost-effective choice for such transitions.

However, a considerable number of SIDS lack access to geothermal energy as a baseload generation source or hydropower for energy storage and potential generation. These SIDS, akin to Aruba, predominantly rely on intermittent renewable energy resources such as wind and solar. The impact of the identified dunkelflaute on other SIDS has not been addressed in current literature. However, given that Aruba possesses above-average wind and solar resources [110], it is plausible to infer that other SIDS may face similar challenges when transitioning to fully renewable energy systems. Specifically, the challenge currently lies in the economic feasibility of such transitions, as achieving a fully renewable energy system would necessitate substantial storage capacity to manage the periods of dunkelflaute, or the implementation of pre-commercial stage technologies such as OTEC to provide a stable renewable baseload.

For SIDS with access to ocean thermal energy resources, OTEC presents a potentially viable solution, particularly if pre-commercial scale plants are constructed in the coming years. The deployment of these plants could facilitate a reduction in future construction costs through learning curves, thereby enhancing the economic viability of OTEC as a renewable energy source.

8.5. Limited local institutional capacity

When evaluating the feasibility of implementing a new technology such as OTEC in Aruba, it is important to take the country’s limited size and the associated consequences into consideration. With a population of 108,000 people [242], comparable to that of an average city in the Netherlands [243], Aruba faces limitations in its local institutional capacity. This term refers to the ability of Aruba’s governmental agencies, regulatory bodies and local institutions to effectively manage, regulate and oversee large-scale infrastructure projects like a commercial-scale OTEC plant [244]. In SIDS such as Aruba, limited institutional capacity can create bottlenecks, impeding the successful deployment of large RET projects.

A robust regulatory framework is essential for aspects such as ensuring compliance with environmental standards, construction safety and operational efficiency in large RET projects. However, SIDS often lack such frameworks or the expertise needed to develop them to effectively govern these projects [9]. This challenge is exacerbated by limited human resources; smaller populations generally result in fewer skilled government employees or regulatory staff capable of managing complex projects. Inadequate staffing, insufficient technical knowledge in energy project management and the inability to attract and retain specialists with the expertise necessary to oversee high-tech initiatives further hinder SIDS' ability to effectively govern large-scale projects [9].

Moreover, OTEC projects typically require substantial upfront capital, necessitating a strong financial oversight structure to ensure transparency and accountability when handling significant international loans or grants. SIDS often struggle in this regard due to a lack of well-established institutions to monitor financial flows, which can lead to risks such as mismanagement, corruption and inefficiencies [245]. Additionally, due to their limited financial and technical resources, SIDS often rely on partnerships between governments, local utility companies and private sector actors to facilitate the construction of RET projects. While these partnerships can provide the necessary resources, they also require effective institutional capacity to manage contracts, ensure accountability and monitor the progress of IPPs. Inadequate institutional capacity within SIDS can lead to inefficiencies, cost overruns, or contractual disputes in such contexts [246].

Collaboration between the Government of Aruba, Utilities Aruba and private sector actors—through mechanisms such as power purchase agreements or *Private Public Partnerships* (PPPs)—could be beneficial in providing the expertise and resources required for the construction of OTEC facilities but requires sufficient institutional capacity to ensure it functions effectively [247]. Such cooperation may, for example, facilitate the process of securing subsidies, with IPPs contributing regulatory expertise to help navigate the complexities of international financial institutions' subsidy applications. This is particularly valuable given that SIDS often lack sufficient in-house expertise to manage these financing structures and regulatory frameworks effectively.

In summary, Aruba's small size and the corresponding limitations in institutional capacity must be considered when further assessing the feasibility of implementing OTEC. While this analysis indicates that OTEC could be technically and economically viable, the complex institutional requirements necessary to support its implementation must also be carefully evaluated when further exploring the implementation of OTEC on Aruba and comparable SIDS.

8.6. Global development of OTEC past pre-commercial phase

SIDS have been identified as possessing some of the most favourable ocean thermal resources globally [13], positioning them as prime candidates for the development of the first commercial OTEC plants. However, these islands often lack the necessary expertise and financial resources to undertake the construction of OTEC facilities at a commercial scale, which is crucial for the broader advancement of this technology. The involvement of multinational companies, potentially in collaboration with research institutes, is likely to be pivotal in providing the knowledge and technical support required by SIDS to develop OTEC plants. Additionally, these companies, in partnership with international climate funds, are expected to play a critical role in securing the necessary financing for these projects.

Advancing OTEC beyond the pre-commercial phase (larger than 10 MW) would greatly benefit from cooperation at an international level, with a multinational company acting as an intermediary between local stakeholders and international knowledge and monetary resources. This process would likely involve a multinational selecting an SIDS, focusing on factors such as high local electricity prices, proximity to deep water and the availability of technical expertise either on the island or nearby.

Moreover, international financial support would significantly enhance the economic feasibility of these projects, as the first commercial size plants are expected to have LCOE figures in excess of current market levels [39]. Assistance from climate funds, for example, would be instrumental in supporting the global development of OTEC and in facilitating the necessary steps to transition OTEC into a commercially viable RET.

8.7. Reflection on scientific relevance

Scientific Relevance

This work introduces two novel contributions to existing methodologies. Firstly, the combination of energy system modelling with a stakeholder and institutional analysis and secondly the focus on dunkelflaute on SIDS and its implication on islands ability to transition to fully renewable energy systems.

This study integrates three key components: a techno-economic analysis, a power system model and a stakeholder analysis. The inclusion of a stakeholder analysis alongside the techno-economic and power system modelling is inspired by the work of Meschede et al. (2022) [11], which identifies a gap in literature on 100% renewable energy system modelling. Specifically, Meschede et al. highlights that social aspects, including stakeholder engagement and public acceptance, are often inadequately addressed in existing studies. This research seeks to contribute to filling this gap by not only assessing the power system model in conjunction with technical analysis but also by incorporating stakeholder engagement and public acceptance of RETs in Aruba through a stakeholder and institutional analysis. This approach aligns with the principles of comprehensive engineering, which considers not only technical but also societal and economic factors.

Furthermore, this work identifies and focuses on occurrences of dunkelflaute in Aruba, defined as extended periods of low renewable resource availability. Previous works by Sabovčik et al. [85] and Jing et al. [86] have started to addressed the impact of dunkelflaute in mainland Europe in countries like Germany, where it presents a notable challenge to the renewable energy transition. However, the analysis of dunkelflaute within the context of SIDS, which often have isolated grids and limited options for renewable baseload energy and storage solutions, represents a novel and underexplored area in literature.

Reflection

Reflecting on the methodology, the integration of stakeholder and institutional analysis with techno-economic and power system modelling significantly enhanced the study's ability to present a more complete and realistic evaluation of OTEC's feasibility in Aruba. This is particularly relevant in the context of SIDS, such as Aruba, where individual local stakeholders, such as specific government officials, play a crucial role in determining the direction and success of the transition to fully renewable energy systems and the choice of technology. By incorporating insights from the stakeholder and institutional analysis, the findings of the power system model are refined and their validity strengthened.

Furthermore, the analysis of dunkelflaute in Aruba emphasises the significant implications these events have on Aruba's, and more broadly SIDS', ability to transition to fully renewable energy systems reliant solely on intermittent renewable energy sources such as wind and solar. It is found that these periods necessitate either the deployment of large-scale energy storage solutions or the integration of a consistent baseload technology such as OTEC, as SIDS akin to Aruba often have very limited options for renewable baseload resources.

To further improve the approach, the stakeholder and institutional analysis could be conducted earlier in the research process, allowing its findings to be more deeply integrated into the power system model. For instance, the discovery that Aruba has entered into a "take or pay" agreement with LNG provider Eagle LNG for 50% of its annual demand could be more thoroughly incorporated into the model, thereby enhancing the comprehensiveness and relevance of the model's outcomes.

8.8. Reflection on social relevance and recommendations

The societal relevance of this work lies in its overarching theme of advancing RET development and implementation to combat climate change. SIDS, such as Aruba, are among the most vulnerable regions to the impacts of climate change, including sea level rise and extreme weather events. These effects threaten to render SIDS uninhabitable by the end of the century unless decisive action is taken to mitigate global warming [9]. Additionally, the capacity to provide a reliable baseload of energy is beneficial for enhancing energy security in SIDS, which have historically relied on price-volatile imported fossil fuels. Given the slow progress in OTEC development in recent years, this work aims to contribute by raising awareness and building confidence in the economic potential of OTEC, particularly at larger scales within a fully renewable energy system. Furthermore, it seeks to assist energy sector stakeholders in Aruba in planning and designing future energy system developments.

Reflecting on this objective, the findings from this study demonstrate that OTEC could be economically viable within a fully renewable energy system in Aruba. The knowledge generated through this research aims to bolster confidence in the economic feasibility of renewable energy technologies in general, and OTEC in particular, thereby facilitating Aruba's energy transition. Consequently, this work contributes positively to the societal goal of advancing Aruba's energy transition.

To further emphasise the societal relevance of this work, the following recommendations are provided for relevant stakeholders. These recommendations are intended to enable key actors to make well-informed decisions regarding the implementation of OTEC in Aruba.

Government of Aruba

- Establish clear targets for achieving a (near) 100% renewable energy system by 2050, including the development of a detailed roadmap for the transition. This should involve close collaboration between Utilities Aruba and the Government, particularly the Ministry of Labor, Integration and Energy and Minister of Economic affairs, Communication and Sustainable development. Such planning is essential for addressing long-term challenges, including storage requirements for integrating large amounts of intermittent energy sources and the future deployment of baseload technologies such as OTEC.
- Take into consideration the impact of dunkelflaute, periods of low solar and wind resource availability, on Aruba's future fully renewable energy system. Addressing this challenge will require either substantial storage capacity or the integration of a technology capable of providing a constant baseload.
- Enhance Aruba's policy framework by building on the government's existing sustainability initiatives, such as the 'Energie Nota' and 'Nationaal Actieplan', to strengthen the country's commitment to advancing renewable energy solutions.
- Strengthen the investment climate in the renewable energy sector by implementing government policy adjustments, such as reducing import duties and considering tax incentives for companies engaged in and supporting the energy transition.
- Set up an independent regulator for Aruba's power sector, similar to the Autoriteit Consument en Markt (ACM) in the Netherlands and Bonaire. This would ensure transparency in decision-making, better regulate the development of renewable energy projects, and provide clarity to external stakeholders, thereby increasing confidence in the sector.
- Designate or hire a governmental official responsible for translating action plans developed in Aruba into formats that align with the requirements and standards of the European Union, international governmental organisations and/or the Dutch government. This role would streamline intergovernmental processes and enhance the facilitation of international aid, such as project funding, to support the transition to renewable energy sources.
- Be careful to extend the 'take or pay' LNG contract with EagleLNG beyond its expiration date to create more economically viable opportunities for the integration of RETs.

Independent Power Producers

- Apply for financial aid programs from international funds such as the EU's Horizon Europe and NER300 or Dutch funds such as the SDE++ and in the future possibly the DEI+ to increase the financial viability of an OTEC project.
- Establish strong relationships with local political parties and individuals to enhance government support, as endorsements can significantly influence policy decisions on the island.
- Leverage the expertise of experienced companies, such as Makai Engineering and Xenesys Inc., that specialise in OTEC or its components to minimise technical development risks and gain valuable insights.
- Examine historical cases from the US and Japan to gain practical insights into implementation aspects, such as CWP installation, and consult institutions like Saga University for empirical data on for example maintenance practices.

WEB and Elmar

- Consider incorporating 'take or pay' or 'capacity based compensation' clauses in power purchase agreement for renewable energy projects, similar to those used in the LNG contract and Vader Piet Windfarm [110], to enhance financial security and attractiveness for independent power producers.
- Assess potential connection points for integrating OTEC into the electricity grid, such as the Vader Piet windfarm substation, and evaluate the required upgrades to the substation capacity that would be necessary.

8.9. Limitations

8.9.1. Development stage of OTEC technology

The model developed in this work assumes that OTEC technology has progressed to a commercial phase, with the deployment of 136 MW OTEC plants. The power system model results suggest that a total OTEC capacity exceeding 200 MW would be cost-optimal, necessitating the construction of two 136 MW plants. However, as of the time of writing, OTEC remains in a pre-commercial phase, with ongoing development efforts aimed at constructing OTEC plants with capacities of 1+ MW in regions such as São Tomé, South Korea and India [7][6]. Since the primary focus of this study is the year 2050, it is assumed that by this time, OTEC technology will have matured to this extent. This assumption is supported by work from Vega [39], which indicates that the construction of plants of this scale is currently technically feasible. Nonetheless, the success of ongoing pilot projects is crucial in bridging the "valley of death" and generating operational data to enhance investor confidence in the technology, playing a key role in determining whether OTEC can advance to the commercial stage.

8.9.2. Focus of the model on the power sector

The model developed in this work focuses solely on the power sector. While this approach provides valuable insights into the functioning of a fully renewable electricity system and enhances the understanding of OTEC's role at the power system level, it does not capture the full complexity of real-world interactions. Notably, the model does not account for sector coupling, which involves integrating the power sector with other energy-consuming sectors such as heating, cooling, transportation and industrial processes [248]. A next step toward such a more comprehensive total-energy-system model for Aruba could involve incorporating hydrogen as a versatile resource, which could be utilised for various purposes, including transport, energy storage and heating and cooling applications [165, 166].

Furthermore, the broader implications of the food-water-energy nexus are not considered in this analysis. This concept refers to the interdependent relationship between these three sectors, where changes or disruptions in one can significantly impact the others [249]. As a consequence, this analysis for example does not account for the potential use of RETs to produce freshwater via reverse osmosis, which could enhance the economic viability of these technologies, given Aruba's lack of natural freshwater sources. Additionally, OTEC produces nutrient-rich and relatively cold DSW as a byproduct. This DSW could be repurposed for agricultural and aquacultural applications due to its nutrient content, and used as a coolant in air conditioning systems due to its low temperature post-OTEC process [250, 251]. However, considering that this study focuses on a floating closed-cycle OTEC configuration, likely situated 15 km offshore, the costs associated with transporting DSW to shore via pipelines would need to be examined further to determine if these costs could be offset by the potential revenue from additional income streams.

Moreover, OC-OTEC has also been explored and has demonstrated feasibility in the past, with desalinated water as a potentially economically advantageous byproduct. However, similar to the reasoning applied above for DSW, OC-OTEC has not been included in the model. For a floating plant, the transportation of desalinated water to shore via pipelines would incur additional costs. Furthermore, current developments in the OTEC field show a predominant focus on CC-OTEC, likely due to its higher efficiency compared to the OC variant [69]. Additionally, CC-OTEC systems have a higher technical capacity feasibility, with potential to scale up to 100 MW, compared to the 2.5 MW expected for OC-OTEC systems [252].

8.9.3. Considerations concerning Aruba's power transmission system

The model employs a copperplate approach, wherein the demand and supply are simulated as a single node. As a result, it does not naturally account for the transmission and distribution components of the grid, which primarily consist of transmission lines, substations and distribution networks. Transmission and distribution losses are incorporated into the model by applying the 16% losses identified by Moorman [126] to the demand profile and compared with 5% and 20% transmission losses in Appendix F. However, the costs associated with constructing and maintaining this infrastructure are not included in the model and are not reflected in the resulting LCoS.

Additionally, the model does not consider the specific geographical locations of power plants. This implies that each new capacity addition incurs uniform costs based on the type of technology, irrespective of whether new transmission lines would need to be constructed in reality. Therefore, the capital costs associated with building transmission lines from the power plants are not incorporated into the LCoS. However, in the case of the OTEC plant, the costs of submarine transmission cables from the plant to shore are included, as they constitute a significant portion of the total capital expenditure. Nonetheless, the costs associated with potential transmission cables from the shore to the substation are not considered.

8.9.4. Uncaptured behind the meter systems

The power system model consists of utility scale generation technologies owned and operated by power producers. This does not include behind the meter power production such as rooftop solar PV systems on residential and commercial buildings and small battery systems. A recent surge in popularity has increased the amount of installed rooftop PV in Aruba. As of 2024 there is a total installed capacity of 22 MW of rooftop PV in Aruba [110]. The installation of these systems is steadily increasing, however the local electricity distribution company Elmar has set maxima to the allowed installed capacity of 10kW for domestic lots and 100kW for business lots [253]. The inclusion of Rooftop PV may result in a slightly different system wide electricity mix as there is a base already installed, which is expected to grow in the future. However, the impact of this is anticipated to be minimal, with a modest effect on OTEC implementation. As demonstrated in the alternative scenario modelled in Chapter 6, increasing land availability resulted in a higher deployment of solar PV, but not to its maximum potential.

8.9.5. MERRA-2 capacity factor profiles for wind and solar

The model uses capacity factor profiles to assess the wind and solar resource availability. These capacity factor profiles are derived from Renewables.ninja, which uses uncorrected MERRA-2 reanalysis to construct power profiles. MERRA-2 is a global atmospheric reanalysis dataset that offers four-dimensional climate data (spatial dimensions: x, y, z; and temporal dimension: t) widely used in climate and atmospheric research [254, 255]. The dataset is however somewhat outdated compared to the reanalysis dataset ERA5 which has a higher spatial resolution and is found to have higher correlations and lower mean absolute errors for most parameters such as wind shear (variation in wind speed or direction over a short distance in the atmosphere)[256]. Consequently, the wind and solar PV capacity profiles derived from Renewables.ninja will show discrepancies when compared to ERA5. These differences are likely to be most pronounced in wind speed data, which directly influence the wind power profiles [255, 257]. For solar PV, it has been observed that ERA5 provides more accurate performance under cloudy-sky conditions, while MERRA-2 performs better under clear and intermediate-sky conditions [258, 259].

8.9.6. Cost assumptions

The cost assumptions incorporated into the model heavily influence the LCOE and LCoS derived from the power system model. As no specific cost data for the construction of RETs in Aruba, either current or future projections, are available in scientific or gray literature, cost assumptions for the utility based PV, floating offshore PV, onshore wind, offshore wind and BESS in this study are based on estimations for Indonesia from the Ministry of Energy and Mineral Resources [134]. Given that Indonesia, like Aruba, is an island nation expected to import these technologies, it is assumed that the costs are comparable. However, this assumption has its limitations as it does not account for differences in factors such as labor costs, import taxes and land costs.

Furthermore, given that no OTEC facilities at the scale proposed in this study (100 MW or greater) have been constructed to date, these cost assumptions cannot be validated against real-world projects. Since OTEC is still in the pre-commercial development phase, there remains uncertainty regarding its eventual costs at a commercial scale. However, there is general consensus within the industry that the technology will become more cost-effective per megawatt as scale increases [39], which is considered in this work as the capital expenditure and operational expenditure figures are derived from pyOTEC that considers component costs, economies of scale and projected learning curves over time [128].

8.9.7. Stranded costs of past investments

The power system model constructs a cost-optimal energy system from the ground up, thereby excluding the costs of past investments, such as the RECIP generator and gas turbines, which may still be operational at that time. Depending on the state of Aruba's generation mix in 2030, 2040 and 2050, these assets may need to be prematurely decommissioned, leading to decommissioning costs or "stranded costs." Stranded costs arise when a plant, still capable of functioning, is retired before the end of its economic life due to external factors such as a shift to renewable energy.

These stranded costs are not accounted for in the model, potentially resulting in additional expenses associated with the early retirement of non-renewable energy generators. It is important to note that the model primarily focuses on the year 2050. Given the typical operational lifespan of 25-30 years [134], the current plants operated by Aruba's electricity company, WEB, would be nearing the end of their service life by 2050. For instance, the most recent RECIP engine (RECIP IV) was installed in 2022 [260]. This juncture may present a critical opportunity for the country to transition from fossil fuel-based generators to renewable energy alternatives.

8.9.8. Marine traffic activity

The model does not account for marine activities surrounding Aruba, which may include commercial shipping routes or offshore tourism activities such as sailing and scuba diving. Preliminary observations of marine traffic in the area suggest that container ships frequently pass north of the island, while oil, container and passenger ships are often present off the west coast, likely awaiting docking at one of Aruba's ports, all of which are located on the island's western side [261]. These activities could influence the site selection for the OTEC plant, as potential conflicts of interest may arise.

It is important to note that the most suitable locations for OTEC implementation are found off the east coast, where marine traffic is relatively modest compared to the northern and western coasts. Consequently, it is anticipated that marine activities will have a limited impact on the implementation of OTEC in these areas.

8.9.9. Limited number of stakeholder interviews

To evaluate the stakeholder findings, expert consultations were conducted with two individuals. The first expert possesses extensive knowledge of OTEC and its potential application in Aruba, while the second expert has a deep understanding of Aruba's energy system and the internal stakeholder dynamics involved. These interviews help to validate the stakeholder analysis, ensuring that the results provide valuable insights into the stakeholders relevant to OTEC implementation in Aruba. However, the stakeholders being interviewed cannot capture all involved groups due to the limited number of interviewees and the temporal limitation of this research.

Firstly, the consulted experts did not include representatives from the private sector specifically focused on OTEC development. Although the first interviewee previously worked in this sector and is knowledgeable, they are no longer employed there. The private sector plays a pivotal role in advancing OTEC to the commercial stage, and its involvement is crucial for successful implementation. Currently, there are no active companies pursuing OTEC projects in the Caribbean; however, historical projects such as Bluerise in Curaçao [262] and Akuo in Martinique [263] demonstrate past interest in the region.

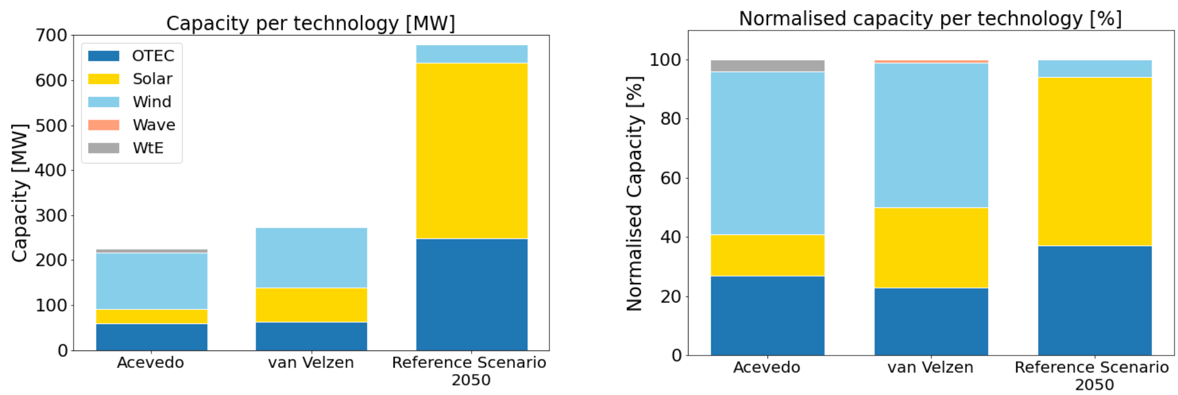
Secondly, the stakeholders consulted did not include representatives from environmental NGOs, which have previously expressed opposition to the implementation of RETs, particularly onshore wind turbines. These NGOs have raised concerns about potential health and environmental impacts on residents and the surrounding natural areas [203]. Such opposition has had tangible effects, as evidenced by the halting of the Urirama Windfarm construction in 2018 [110], highlighting the capacity of these groups to influence the development of RETs. However, during the consultations, the first interviewee noted that the influence of these NGOs is significantly dependent on the stance of the government. For instance, despite vocal opposition, the construction of the new LNG terminal by Eagle LNG has proceeded [110].

Lastly, none of the stakeholders were affiliated with international funding organisations. The second interviewee pointed out that Aruba occupies a ”gray area” when seeking funding or subsidies. Its status as a constituent country within the Kingdom of the Netherlands excludes it from eligibility for regional investment banks such as the Inter-American Development Bank (IDB). Moreover, Aruba’s relatively strong economic standing reduces its chances of accessing funds and financial mechanisms like the Green Climate Fund (GCF), which are primarily targeted at developing countries. Gaining a clearer understanding of how Aruba fits within these organisations’ criteria could provide valuable guidance for advancing OTEC implementation on the island.

8.10. Validation model findings

To validate the model findings, the results were compared to similar master thesis studies exploring the renewable energy transition of Aruba that include OTEC. The primary references for this comparison are the works of Acevedo (2016) [70] and van Velzen (2017) [71]. Acevedo and van Velzen both employ a custom-designed MATLAB model to simulate Aruba’s power system, optimising for minimal total system costs. These models perform multi-objective optimisation, aiming to determine the most cost-effective renewable energy system by minimising overall system costs. Both studies conclude that OTEC is an economically viable component of a system with high renewable energy penetration in Aruba. Acevedo’s work models a fully renewable energy system, while van Velzen’s study explores a 90% renewable system.

Acevedo and van Velzen examine Aruba’s power system as of 2016 and 2017, respectively. Consequently, the demand and therefore total system capacity in their analyses are lower than those considered in this study, which focuses on the projected conditions for 2050. To account for these differences, both the absolute capacity and total electricity generation per year (as presented in Figures 8.2a and 8.2b) and their normalised values (illustrated in Figures 8.3b and 8.3b) are compared to the 2050 reference scenario of this work. The normalised values provide a more meaningful basis for comparison.

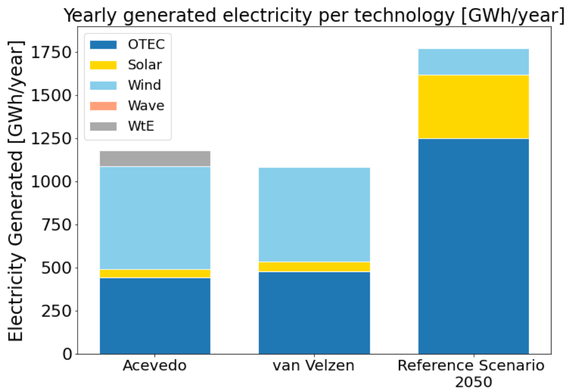


(a) Capacity results of each work.

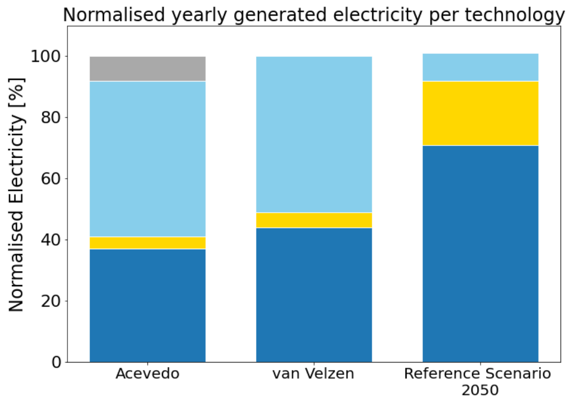
(b) Normalised capacity results of each work.

Figure 8.2: Capacity comparison between each work, absolute and normalised.

Upon examining the normalised capacity values in Figure 8.2b, it is observed that the normalised share of OTEC capacity is comparable across the studies, ranging between 27% and 37%. The most significant difference is a shift from wind to solar energy. The slightly higher OTEC share in this study is likely attributable to the reduced capital expenditure assumed for OTEC, reflecting the larger scale of the plant. Furthermore, the larger share of OTEC is also attributed to the high costs associated with BESS required when integrating more solar PV and wind into the system as a result of the dunkelflaute identified in this work. The shift from wind to solar energy is expected to be driven by the substantial decrease in the cost of solar PV installation in recent years, with installation costs nearly halving since 2017 [189]. Whilst wind energy has also seen cost reductions, these have not been as pronounced.



(a) Yearly generated electricity of each work.



(b) Normalised yearly generated electricity of each work.

Figure 8.3: Yearly generated electricity comparison between each work, absolute and normalised.

When comparing the normalised total electricity generation, it is observed that the proportion of electricity generated by OTEC in this work is relatively high. This is likely due to OTEC's high capacity factor and its role as a baseload generator. Since OTEC is designated as a baseload resource, the Calliope model may be economically incentivised to prioritise its deployment, thereby limiting the use of other RETs. As a result, OTEC generates more electricity compared to solar or wind installations, which are more variable in nature.

The comparison of results with previous studies reinforces the inclusion of OTEC in a 100% renewable electricity mix in Aruba, supporting its role in Aruba's energy transition.

9

Conclusions and Recommendations

In this chapter, concluding answers to the research questions are presented in Section 9.1. This is followed by recommendations for future research and the industry in Section 9.2.

9.1. Revisiting the research questions

9.1.1. Answering sub research question 1

What is the state of the art of OTEC's technical and economic potential and of modelling fully renewable SIDS energy systems?

The current state of OTEC technology reflects its position in a pre-commercial phase, with operational plants historically ranging from a few kilowatts to 1 MW in capacity. To transition OTEC to a commercial stage, substantial investments are required for the development and construction of larger plants. Companies such as Global OTEC and Makai Engineering are actively contributing to the development of commercial-scale CC floating plants. It is reported that 10-50 MW floating, CC-OTEC facilities are technically feasible using current design, manufacturing, deployment techniques and materials. Further investigation into the implications of the large amount of discharge water is necessary for OTEC plants with capacities exceeding 100 MW. Plants with capacities ranging from 20 MW to 100 MW, have been proposed in literature, indicating the potential for scaling up the technology.

Experience gained from constructing smaller commercial plants (1-10 MW) is expected to be highly beneficial in optimising technical aspects associated with scaling up, particularly in the areas of CWP, heat exchangers and thermodynamic cycles. Additionally, recent studies have identified regions with technically feasible sites where the LCOE for commercial OTEC plants could be as low as 0.15 USD(2021)/kWh.

In the short to medium term, SIDS have been recognised as key niche markets for OTEC deployment, given their access to warm sea surface waters and reliance on expensive fossil fuel-based electricity generation. These regions represent strategically advantageous entry points for OTEC, offering the opportunity to develop economically viable pilot plants that could aid research into achieving cost reductions, improve the technology's economics. By focusing initial efforts on these regions, OTEC can be positioned for broader adoption in the future.

For the state of the art of modelling fully renewable SIDS energy system it is found that the role of OTEC in renewable island energy systems is largely overlooked in current modelling research. Only a few geographical locations, such as La Réunion and Indonesia, have been identified where OTEC was included in the analysis. Instead, the majority of research has concentrated on wind energy, solar energy, battery storage and, where applicable, hydro storage and geothermal energy. Additionally, these energy system studies frequently fail to address social aspects, such as stakeholder engagement and public acceptance, which are critical for the successful implementation of RETs on SIDS.

9.1.2. Answering sub research question 2

What is the technical potential of CC floating OTEC and other renewable technologies in Aruba and how do they compare economically?

Five RETs were identified as viable for deployment in Aruba including onshore and offshore wind turbines, utility-scale land-based and floating solar PV and OTEC. Additionally, BESS has been identified as a storage solution. The primary limiting factor for the capacity is land availability. Due to the island's high population density and the designation of a significant portion of the land as protected nature reserves, the availability of land for renewable energy development is severely restricted. It is estimated that approximately 9 km² of land is available for onshore wind and solar PV together, which translates to a maximum capacity of 89 MW for onshore wind and 389 MWp for utility-scale land-based solar PV. In contrast, Aruba's extensive offshore EEZ provides access to abundant offshore renewable energy resources. Additionally, a recurring annual period of simultaneously reduced solar and wind resources, known as "dunkelflaute," has been observed, necessitating significant amount of storage for intermittent RETs in a fully renewable energy system.

An economic comparison of these technologies for the year 2021 reveals that the LCOE for onshore wind and solar PV is the lowest, followed by fossil fuel alternatives. Floating PV, offshore wind and OTEC are found to be more expensive than fossil fuels, with OTEC being the most costly. However, when the necessary storage capacity required to achieve a fully renewable energy system is considered, OTEC becomes more economically viable, as the substantial costs associated with the required storage significantly impact the overall system economics. In this case, an 80 MW OTEC plant has the lowest LCOE amongst the RETs.

9.1.3. Answering sub research question 3

What are cost-effective configurations for Aruba's future renewable electricity system under varying techno-economic assumptions and scenarios and what is OTEC's role in them?

Evaluating the cost-optimal configurations of Aruba's future renewable electricity system, it is found that OTEC has the potential to become a large component in Aruba's energy mix consisting of 249 MW of OTEC in 2050 with an LCOE of 106 USD/MWh, generating 70% of Aruba's total electricity demand. Furthermore, OTEC demonstrates a significant presence across most of the evaluated scenarios, suggesting its potential role in a wide range of future scenarios. The scalability of OTEC technology is essential for its economic viability: at 10 MW it fails to remain cost effective without subsidies, necessitating a minimum capacity of 35-40 MW plant size.

Across scenarios, OTEC and utility scale land based solar PV are the dominant generators, with onshore wind only becoming significant when fossil fuels are introduced to the system. This observation can be attributed to the greater volatility of wind energy compared to solar PV systems, which necessitates increased battery storage capacity and consequently results in higher associated costs. OTEC's implementation is found to be strongly dependent on the amount of fossil fuels allowed in the system with OTEC no longer being cost competitive with a renewable generation mix lower than 50%.

Implementing OTEC could save up to 107 million USD per year (on a levelised basis) versus the cheapest alternative 100% RET case, but cost 44 million USD per year more compared to the scenario with no restrictions on fossil fuels. Set against a total GDP of some 4.0 billion USD per year these are not insignificant amounts.

9.1.4. Answering sub research question 4

Who are the important stakeholders and how can they promote or obstruct OTEC's development?

Aruba has a complex network of stakeholders, which would need to interact to facilitate the implementation of OTEC. The most important identified stakeholder is the Government of Aruba as it holds the most power to help but also to hinder OTEC's implementation. This influence is exerted through legislative actions, the issuance of necessary permits and policy decisions and most importantly the government's influence over the state-owned holding company, Utilities Aruba, which oversees WEB and Elmar. WEB and Elmar play critical roles in electricity generation and distribution on the island, with WEB owning and operating most of the generation facilities and Elmar holding exclusive concessions to distribute and sell electricity to end consumers.

Furthermore, it is expected that involving an IPP as project developer would be beneficial to OTEC's implementation. The IPP operates as a central stakeholder connecting all required actors that would aid OTEC's implementation such as technical advisors and financial institutions.

It is found that although Aruba displays favourable conditions for OTEC that would drive its implementation such as a demonstrated political and economic stability in the country and good environmental conditions for OTEC, there are certain barriers to take into consideration. The most important ones are the recent LNG "take or pay" deal between the Government of Aruba and Eagle LNG limiting Aruba's renewable energy share to 50% for the next 20 years, a limited commitment of the government to transition to a fully renewable energy system and the historic resistance from certain environmental NGOs against renewable energy projects. For the successful implementation of OTEC these barriers will have to be addressed.

9.1.5. Answering main research question

Is it technically and economically feasible to implement OTEC in Aruba's energy system and if so what technical, economic and social factors play a role?

Modelling Aruba's power system suggests that the implementation of OTEC could be technically and economically feasible. Moreover, OTEC could play an important part in achieving a fully renewable energy system in Aruba by 2050. Due to its baseload and dispatchable properties, OTEC would significantly reduce the need for large-scale battery storage systems, which would otherwise be necessary in a system reliant solely on solar and wind energy. Consequently, the total system cost of Aruba's electricity infrastructure could be decreased by incorporating an OTEC component compared to a system based exclusively on wind and solar power. The reference scenario estimates an LCoS of 96 USD/MWh with an OTEC capacity of up to 249 MW.

Two conditions are found to be critical for an implementation of OTEC in Aruba. Firstly, the Government of Aruba must establish a clear target to achieve more than 50% renewable energy in its electricity generation mix. Without this commitment, solar and wind technologies would likely suffice, given the limited storage requirements. Secondly, OTEC technology must advance to a commercial phase, leveraging economies of scale to enhance its economic attractiveness. Expert consultations suggest that an optimal plant size for OTEC in Aruba by 2050 would be in the range of 40-50 MW. A high-level roadmap indicates that this target is feasible and aligns with the recently signed 20-year LNG import contract. While increasing the plant size could further reduce the overall system cost, it would also heighten the country's dependence on a single technology and present greater financing challenges.

9.2. Recommendations for future research and industry

Based on the insights, conclusions and limitations of this work, three potential avenues for further research have been identified in 9.2.1, 9.2.2, 9.2.3. Furthermore, 3 practical recommendations to the industry are presented in 9.2.4, 9.2.5 and 9.2.6.

9.2.1. Address limitations and further expand the model

Firstly, future research could address the limitations of the current model to enhance its accuracy and provide more detailed insights. Currently, the model employs a copperplate approach, with transmission losses integrated into the demand curve. A more precise calculation of the LCoS could be achieved by explicitly incorporating transmission and distribution lines into the model. This would allow for the inclusion of additional costs associated with constructing the necessary transmission and distribution infrastructure, as well as a more refined estimation of transmission losses. To accomplish this future research could focus on implementing the identified suitable locations in chapter 5 for the construction of supply technologies both on the island and offshore. This would involve determining optimal geographic sites for connecting these technologies to the grid and mapping current electricity demand nodes, such as the island's largest cities. This spatial analysis would provide a more accurate representation of where energy supply and demand interact, further refining the model's approach to transmission infrastructure.

Another limitation that could be addressed is the exclusion of behind-the-meter systems, such as rooftop solar PV. Integrating these systems into the model would increase the effective land availability for PV installations. Additionally, a more detailed GIS analysis to assess the technical potential of land-based RETs could further validate the model's findings. This would provide more accurate estimates of the required contribution of OTEC and confirm the constraints imposed by limited land resources.

Secondly, future research could also focus on expanding the model to include sector coupling and the food-water-energy nexus to develop it into a more comprehensive total-energy-system model. An initial step could be the integration of hydrogen as a versatile energy carrier in the model. Hydrogen can be produced through electrolysis using power generated by the model's supply technologies and subsequently utilised across multiple sectors. In the power sector, hydrogen could serve as a medium-to long-term energy storage solution [166]. In the transportation sector, it could be employed as a fuel for hydrogen fuel cell vehicles [165]. Additionally, hydrogen could be used in the heating and cooling sector to power these systems, further enhancing the model's capability to represent cross-sectoral energy interactions.

When integrating multiple sectors into the model, such as incorporating freshwater production, it is crucial to consider not only the technical and economic aspects but also the stakeholders and vested interests on the island. Expert consultations highlighted for example that introducing water production via reverse osmosis or employing an OC-OTEC plant to produce freshwater would encroach on the business of WEB Aruba, which is the sole entity legally authorised to produce freshwater. This would necessitate extensive communication and collaboration with both WEB Aruba and Utilities Aruba. Such social and regulatory considerations must also be accounted for to ensure that sectoral integration is both feasible and aligned with existing institutional frameworks.

9.2.2. Explore the implications of "dunkelflaute" on other SIDS

The identified periods of extended simultaneous low solar and wind resource availability have a significant impact on the configuration of Aruba's renewable energy system. Future research could build upon these findings by conducting similar analyses to explore wind and solar resource availability across other SIDS. This would help determine whether such "dunkelflaute" events occur in other SIDS and, if so, what the implications are for those that lack access to renewable baseload technologies such as geothermal or hydro power. Additionally, these studies could assess the applicability of OTEC as a potential solution to provide a stable baseload for such regions.

9.2.3. Incorporate key stakeholder interviews into the qualitative analysis

Future research could expand on the findings of this study by conducting a more detailed investigation of the complex interactions between various stakeholders involved in the implementation of OTEC in Aruba or other SIDS. A particular emphasis could be placed on also incorporating interviews with IPPs to examine their perspectives and understand how they would interact with local and international stakeholders, including local governments and residents, international financial institutions and technology advisors. Their role is identified as crucial for the successful implementation of OTEC. Gaining further insights into their position would help refine the strategy for OTEC deployment in Aruba. Furthermore, additional interviews with local government officials could provide further insight into the plans of the local government for the renewable energy transition. Although the government of Aruba has expressed a commitment to increasing its renewable energy capacity, substantial uncertainty remains regarding how this transition will be achieved, further complicated by local political dynamics. Further studies could also explore the local political landscape of Aruba in greater depth to identify strategies for advancing the renewable energy transition including OTEC.

Additionally, conducting interviews with financial institutions, such as international funding agencies or commercial banks, would provide valuable insights into the processes and requirements for securing financing for the development and construction of commercial-scale OTEC on Aruba. Furthermore, engaging with local NGOs could help gauge public sentiment towards the technology. Given the strong opposition from some NGOs to the construction of a previous wind park, understanding their perspectives and motivations could be instrumental in addressing potential concerns and ensuring smoother project implementation [203].

9.2.4. Consider OTEC's relevance for SIDS at high RET penetration

This analysis concludes that OTEC at a commercial scale can be technically and economically viable from a power system-wide perspective for SIDS such as Aruba, at renewable energy penetration levels as low as 50%. Many SIDS are advancing towards increasingly high renewable energy system shares, with high electricity consumption islands like Mauritius, Haiti and Curaçao currently achieving renewable energy shares of 29%, 17% and 33%, respectively [264]. As these islands continue to increase their renewable energy penetration, OTEC should be considered by the renewable energy industry as a technologically and economically viable option to further enhance renewable integration.

This is particularly important given the challenges posed by intermittency phenomena such as dunkelflaute, which can hinder further transitions at higher levels of RET penetration. As a result of dunkelflaute events, intermittent sources like wind and solar become less economically effective at higher RET penetration due to the increased complexity and cost of the infrastructure needed to maintain system stability [240]. This effect becomes especially significant in the context of fully renewable power systems and may be underestimated at present when not considering longer time horizons with higher RET penetration rates.

Therefore, it is recommended to assess the long-term implications of dunkelflaute on the energy transition of SIDS and address the limitations of intermittent renewables at higher penetration levels by emphasising OTEC as a viable renewable alternative in industry policies. In addition, providing targeted funding for pilot OTEC plants, could help bridge the “valley of death” and accelerate technology development. This approach would ensure that OTEC is sufficiently advanced by the time SIDS encounter barriers to integrating higher shares of RETs, where it may become economically difficult to support increased renewable penetration without a reliable renewable baseload.

9.2.5. Communicate with local government and provide relevant expertise

The stakeholder and institutional analysis in this study indicates that the development and construction of an OTEC plant in Aruba should account for the country’s concentrated power dynamics and limited institutional capacity. Key stakeholders, particularly government ministers, wield considerable influence over decision-making, highlighting the importance of effective communication with these individuals and relevant entities. However, local institutions often face capacity constraints that hinder their ability to perform tasks, such as securing international subsidies and managing large-scale, complex projects.

For future OTEC project development in Aruba, it is recommended that developers establish strong communication channels with key government ministers, relevant political parties and other critical stakeholders such as local NGOs. Engaging in targeted lobbying and stakeholder engagement will be crucial. Additionally, developers should bring in external expertise not readily available within local institutions, particularly in managing large Capex projects and securing international subsidies and financing. This approach will significantly enhance the project’s ability to progress efficiently and effectively.

9.2.6. Compensate OTEC developers based on capacity availability

One of the barriers to OTEC implementation is the high capital investment required. Additionally, this work finds that OTEC’s modelled utilisation factor ranges between 81-82% in the reference scenario, which could restrict its operational capacity and potentially impact project profitability. To mitigate these risks and facilitate OTEC implementation in Aruba, *Power Purchase Agreements* (PPAs) with compensation based on capacity availability, rather than solely on generated energy, are recommended. This would help establish a more stable revenue stream and enhance the overall financial viability of an OTEC project in Aruba and other SIDS.

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A

Detailed description pyOTEC

pyOTEC is a novel Python-based, open source model designed and described by Langer & Blok (2023) [13]. It designs closed cycled, floating, moored OTEC plants for the best economic performance considering the spatiotemporally specific availability and seasonality of ocean thermal energy resources. The model uses 1 year of daily seawater temperature data in 1/12° × 1/12° (≈ 9 km × 9 km) resolution obtained from the Global Ocean Physics Reanalysis by Copernicus Marine Service [123]. The user can define an area of interest and the size of the OTEC plant in kW. For this work Aruba is chosen with a plant size of 136MW$_{gross}$.

pyOTEC is employed to obtain spatially explicit time-series data on the designed OTEC plants and their net power production. These can be used to calculate daily capacity factors which are used as inputs for power system models in addition to identifying locations where the OTEC plant could be placed. A more detailed description of pyOTEC, with the method and materials it utilises is provided in the section below. Furthermore, the Capex and Opex of the designed plant are also computed using pyOTEC.

The methods and materials employed by the model are visualised in Figure A.1 and explained as follows. Firstly, the model performs a site selection analysis, where it removes sites that are unsuitable for OTEC such as sites outside of the regions' EEZ, sites within marine protected areas and sites that don't have water depths between 600-3000m. The remaining sites are considered technically feasible. Then, the distance to the closest coastline is calculated to compute the transmission costs and losses. Finally, the geographic extent of all regions with technically feasible OTEC sites is calculated and the names of the regions as well as their coordinates are stored in a csv file. This file is used to download the seawater temperature data in the next step. Moreover, another csv file is created that stores all technically feasible OTEC sites (N = 218,481 sites.)

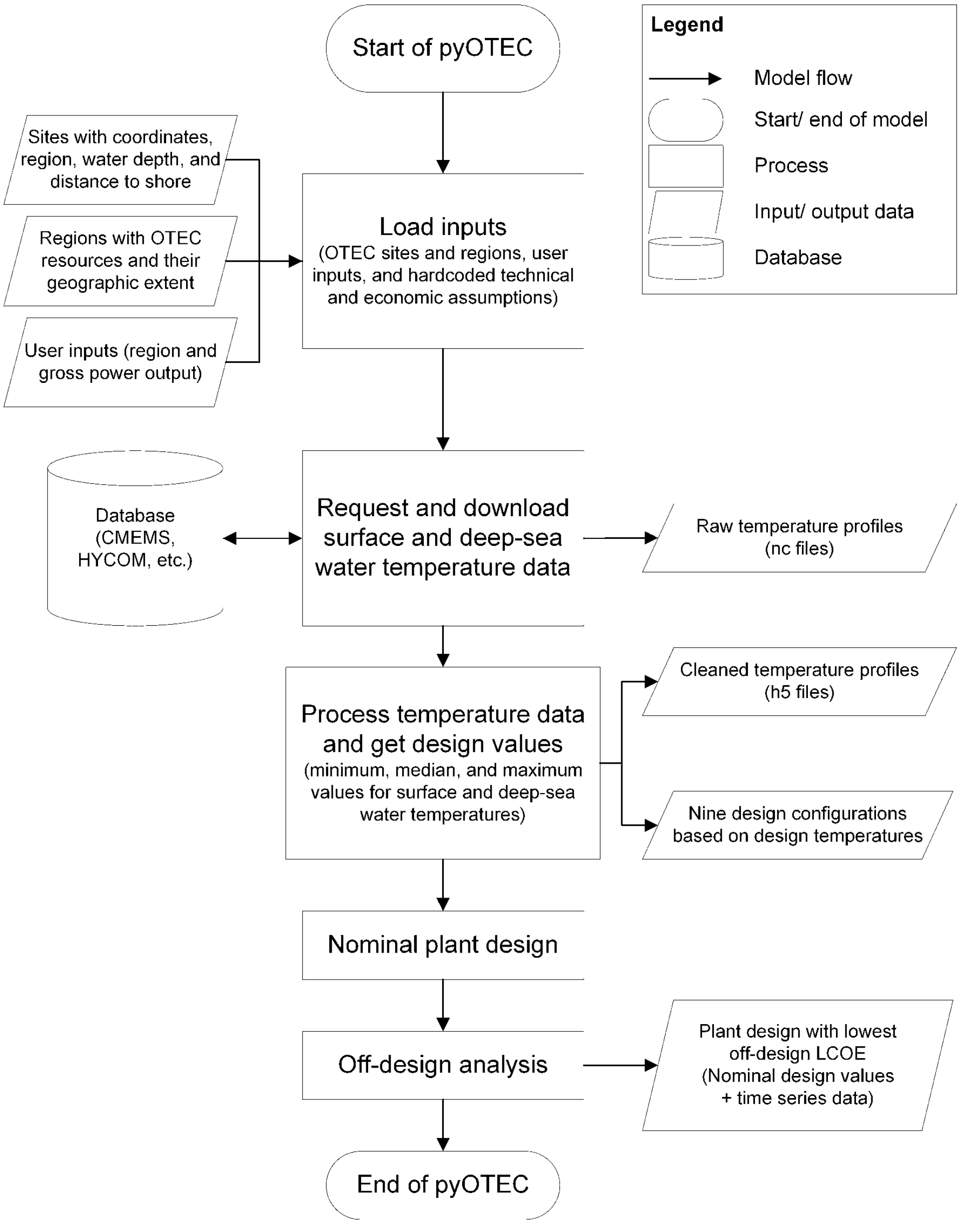

Figure A.1: Flowchart of the pyOTEC model [13].

Once the user provides the area of interest, in this work Aruba, the model downloads the time series data subset for surface and deep-sea water temperatures from Copernicus Marine Service [123], which offers 24 hour time steps from 1993 to 2020. By default pyOTEC requests the full year 2020 data at depths of 21.6m and 1062m, which correspond to the lengths of the warm and cold seawater inlet pipes.

pyOTEC uses the seawater temperature data to calculate the site-specific minimum, median and maximum surface and deep-sea water temperatures. These temperatures are used to perform a two-stage design process consisting of a nominal and off-design analysis.

First, the OTEC plants are sized under nominal conditions, meaning that the plants are assumed to operate solely under design conditions without seasonal seawater temperature variations. The plants are designed using combinations of minimum, median and maximum warm and cold seawater temperatures as inlet temperatures for the evaporator and condenser shown in Figure A.2. To determine the economically best nominal outlet temperatures, pyOTEC loops through 49 combinations of warm and cold seawater temperatures differences between inlet and outlet (from 2 °C to 5 °C in steps of 0.5 °C).

Configuration 1 is the most conservative design based on worst-case temperature values, whereas configuration 9 is the most optimistic design using best-case temperature values.

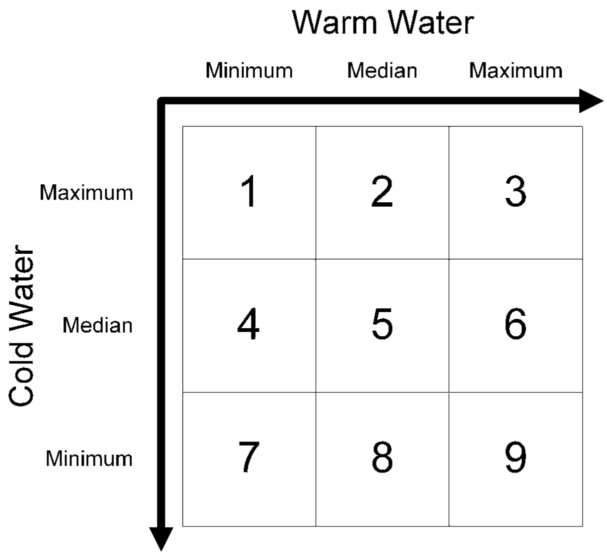

Figure A.2: The nine configurations analysed by pyOTEC [13].

Once the plants have been sized under nominal conditions, pyOTEC calculates the component Capital Expenditure (Capex). To account for OTEC's strong economies of scale Equation (A.1) is employed. This entails that the larger the capacity of the plant, the lower the Capex in USD/MW will be. Here $\dot{W}_{t,gross}$ is the gross power of the plant, b is the scaling coefficient and 0 is the base plant.

$$\text{capex} = \text{capex}_0 * \left(\frac{\dot{W}_{t,\text{ gross },0}}{\dot{W}_{t,\text{ gross}}} \right)^b . \tag{A.1}$$

Once all the component Capex costs have been summed to obtain the system Capex, the model moves on to the Levelised Cost of Electricity (LCOE), which reflects the costs of electricity generation considering all costs in their present value accruing over the plant's lifetime. This results in the nominal LCOE, which assumes that the nominal design conditions, including seawater temperatures, apply continuously throughout the plant's lifetime. The model computes 49 different configurations with corresponding nominal LCOEs. The design (or configuration) with the lowest nominal LCOE, together with its properties, e.g. heat exchanger areas, are handed to the off-design analysis module.

The off-design analysis aims to find the configuration with the lowest LCOE considering the seasonal variations of the ocean thermal energy resources. The important difference between the nominal and off-design analysis is that the latter does not use nominal temperatures but time series data which fluctuates above and below the nominal temperatures.

As there can now be a lack and/or excess of warm and/or cold ocean thermal energy resources the following logic is applied. The evaporation pressure is decreased if the warm seawater temperature is below the nominal temperature; and the condensation pressure is increased if the cold seawater temperature is above the nominal temperature. If there is an excess of warm and/or cold ocean thermal energy resources, the evaporation and/or condensation pressures are kept at nominal values, and instead, the seawater mass flows are decreased, as less seawater is required to evaporate/condense the same amount of working fluid.

After the nominal and off-design analyses are conducted for all nine configurations, pyOTEC returns the configuration with the lowest off-design LCOE [13].

B

Background information on global BESS development

The global installed base of BESS has experienced a dramatic increase over the past decade, growing from approximately 1 *gigawatt* (GW) in 2013 to over 85 GW in 2023. In excess of 40GW was added in 2023 alone. This growth in recent years has been driven almost entirely by China, the European Union and the US, collectively accounting for 90% of the capacity added in 2023 [95] as shown in Figure B.1. Approximately 65% of this capacity addition is for utility-scale systems, defined as large applications connected directly to transmission or distribution networks (front-of-the-meter), typically ranging from several hundred kWh to multiple GWh in size. The other 35% is attributed to smaller behind-the-meter installations, which aren't directly connected to the grid [95].

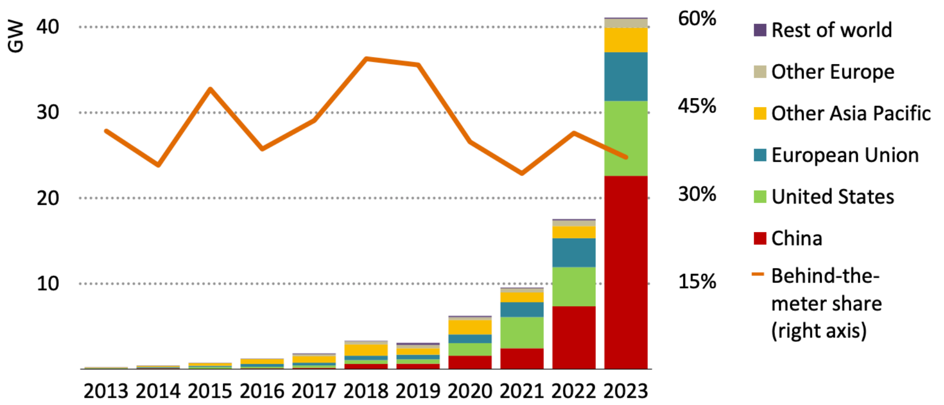

Figure B.1: Installed BESS Capacity Worldwide [95].

An analysis of the current distribution of *energy storage technologies* (EST) reveals that the majority of electrochemical storage systems are based on Lithium-ion technology [124], as illustrated in Figure B.2. Consequently, Lithium-ion systems are the primary focus of this work.

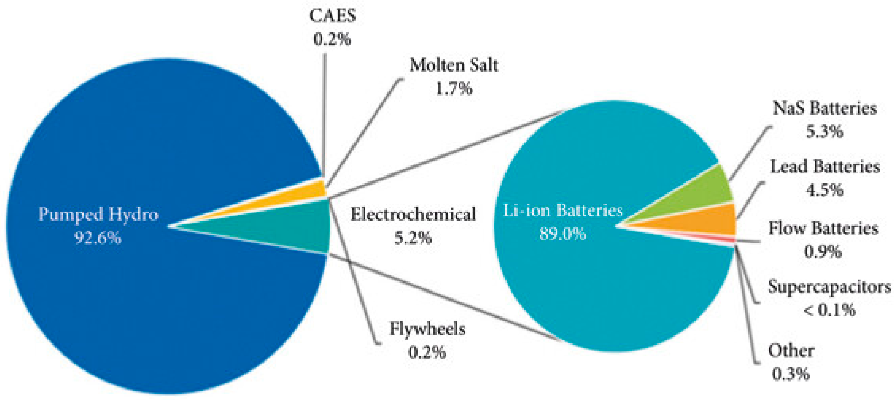

Figure B.2: Global capacity of all EST [124].

C
BESS storage curves

The following battery storage curves are used to determine the solar and wind farm SoC curves depicted in Figure 5.24 and 5.25.

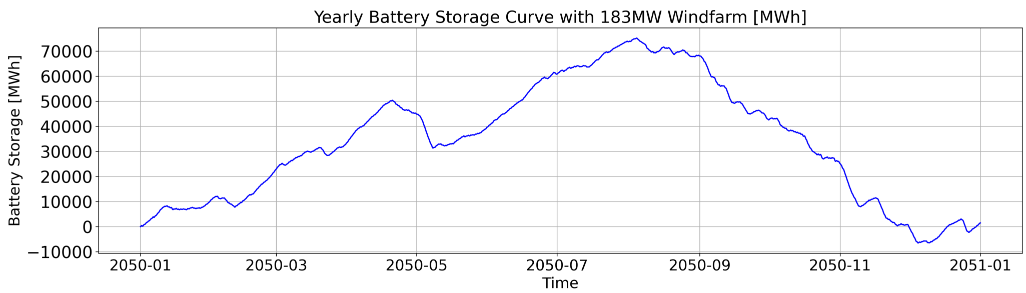

Figure C.1: Battery storage curve for a 183MW wind farm with battery storage on Aruba.

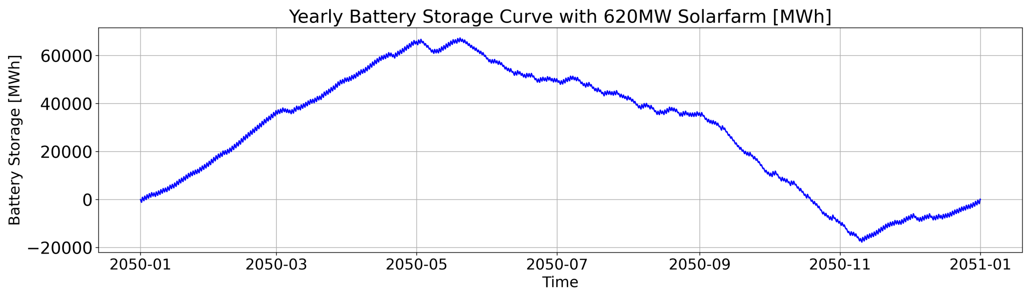

Figure C.2: Battery storage curve for a 620MW solar farm with battery storage on Aruba.

D

List and description of stakeholders

Market

Stakeholder	Role/Description	Stance OTEC
Electricity and Utility Companies Aruba		
Utility Company Aruba N.V.	The parent company of WEB and Elmar. Acts as an intermediary between the government and WEB/Elmar. State owned company who's "leading role is supervising the energy transition towards her working entities" (Croes, 2022)	Neutral
Elmar Aruba N.V.	The sole electricity distributor in Aruba. In charge of the distribution network. Roles wrt OTEC: - Electricity sales/purchase contract - Connection of OTEC to the grid	Neutral
WEB Aruba N.V.	The main electricity generator and freshwater provider in Aruba. Currently provides the island with electricity through (mostly) RECIP generators, gas turbines, wind turbines and solar PV.	Neutral
OTEC Technology Advisers (EPC-)		
OTEC Global	Company specializing in the development and implementation of OTEC technology, specifically in SIDS. Currently developing a 1MW OTEC plant for deployment in São Tomé.	Pro OTEC
Makai Ocean Engineering	Engineering firm specializing in innovative ocean-based technologies. Pioneers in areas such as OTEC, submarine cable deployment, and ocean-based renewable energy projects. Working with Shell.	Pro OTEC
Xenesys Inc	Japanese technology company specializing in the development and implementation of OTEC, with expertise on heat exchangers and power gen unit. Has been/is involved in several pilot projects aimed at demonstrating the viability of OTEC.	Pro OTEC
OTEC Project Developers (Independent Power Producers, IPP)		
Shell Technology – Marine Renewable Program	A global research and development initiative within Shell Global dedicated to advancing marine renewable energy technologies to foster sustainable growth in the Blue Economy. Invest in OTEC development with Makai Ocean Engineering and NIOT.	Pro OTEC
Akuo Energy	A global renewable energy company specializing in the development, financing, construction, and operation of sustainable energy projects. Was connected to the 16MW OTEC project in Martinique. Has shown interest in becoming an EPCI.	Neutral
Mitsui O.S.K. Lines (MOL)	One of the world largest shipping companies, which has invested in OTEC technology as part of its commitment to sustainable development and reducing its environmental impact. Currently developing commercial size OTEC.	Pro OTEC
Ocean Thermal Energy Corporation	U.S.-based company developing OTEC and Seawater Air Conditioning (SWAC) systems. Involved with OTEC production projects the Bahamas, US Virgin Islands and Puerto Rico (Link, Selz (2018)). Mainly operates as a project developer with a strong focus on commercialisation.	Pro OTEC
Financial Institutions		
International Development Banks	At early stages banks such as the Caribbean Development Bank (CDB) and possibly Inter-American Development Bank could provide capital for the high CAPEX OTEC projects.	Neutral
International Commercial Banks	At later stages banks such as HSBC, JP Morgan, Deutsche Bank etc. could be utilised to provide capital for OTEC projects.	Neutral
Commercial Banks Aruba	Aruba has 4 officially recognised commercial banks; Aruba Bank N.V., Banco di Caribe N.V., Caribbean Mercantile Bank and RBC Royal Bank (Aruba) N.V. Due to their size the impact of investment will most likely be small.	Neutral
Alternative RE Developers		
Utility solar PV developers	Responsible for the installation of new solar panels which have seen a large increase over the last few years. They could perceive OTEC as competition and react negatively to its implementation.	Neutral

Wind park developers	Responsible for the installation of wind turbines such as the 30MW "Windpark Vader Piet". Which could perceive OTEC as competition and react negatively to its implementation.	Neutral
Battery Energy Storage System (BESS) developers	Responsible for the development and installation of Battery Energy System Storage (BESS) technology. Biggest competitor for OTEC as it provides an alternative to base-load solutions (with solar and wind).	Threat
Companies operating near OTEC		
Shipping and Cruise Companies	Shipping and Cruise companies utilize shipping lanes that may be located near or on potential OTEC sights.	Threat
Fishing Companies	Fishing companies could operate near the OTEC plant and therefore be opposed to its construction.	Threat
Tourism Industry: Scuba diving	Tourist operating companies that make use of Aruba's offshore waters could be opposed to OTEC's construction.	Threat
Aruba Hotel and Tourism Association	Non-profit association that represents the interests of hotels and other tourism-related businesses in Aruba. Founded with the purpose of advocating for policies and practices with a strong influence on local government.	Neutral

Figure D.1: List of market stakeholders.

Local Government

Government

Stakeholder	Role/Description	Stance OTEC
Ministry of Economic Affairs, Communication and Sustainable Development:		
Department of Economic Affairs, Commerce and Industry (DEZHI)	Advises the Minister on economic policies with focus on sustainable economic development, economic prosperity, and the social welfare of Aruba's inhabitants. And implements these in turn on behalf of the Minister. Important in the drafting of legislation that can boost RE implantation.	Neutral / Pro OTEC
Aruba Investment Agency (ARINA) (Advisory)	Promotes and connects Aruba to global business opportunities to attract pioneer investors, capital, knowledge, and innovative technology in new economic sectors to contribute to the sustainable development of Aruba. Could provide support with the implementation of OTEC.	Neutral
Social and Economic Council (SER) (Advisory)	Advises the Government on all important issues of social and/or economic nature. Appears to be an active player in Aruba's pollical landscape.	Neutral
Ministry Finance & Culture:		
Office for Government Grant Coordination (CBOS)	Issues government grants and monitors how they are implemented.	Neutral
Ministry of General Affairs, Innovation, Government Organization, Infrastructure and Spatial Planning		
Dienst Openbare Werken (DOW)	Public works department of Aruba, responsible for the planning, construction, and maintenance of public infrastructure on the island.	Neutral
Department for Infrastructure Management and Planning (DIP)	In charge of land and water allocation through integrated spatial development and planning. Plays an important role in RE projects for land and water allocation.	Neutral
Department for Technical Inspections (DTI)	Responsible for electrical inspections of the energy system and plants. Additionally, it is closely and actively involved in the environmental policy of Aruba.	Neutral
Ministry of Labor, Integration and Energy		
WEB, Elmar and Utilities Aruba	Role: responsible for overseeing government connections with WEB, Elmar and Utilities Aruba.	Neutral
Ministry of Tourism and Public Health		
Aruba Ports Authority N.V. (APA)	Responsible for marine traffic around Aruba. Could be a threat as sea routes could be located on ideal/preferred OTEC locations.	Threat
Ministry of Transport, Integrity, Nature, and Elderly Affairs:		
Department Nature and Environment	Prepares, designs, and implements policies that lead to a sustainable healthy environment for people and nature in Aruba to preserve, protect and improve natural and environmental qualities. Could work in favour or against RE projects based on the impact on the direct environment.	Neutral
Directie Scheepvaart Aruba (DSA)	Directie Scheepvaart Aruba (DSA) is the maritime authority responsible for regulating and overseeing maritime activities in Aruba.	Neutral

Figure D.2: List of government stakeholders.

International Bodies

International Governmental Bodies

Stakeholder	Role/Description	Stance OTEC
NL Government		
Ministry of the Interior and Kingdom Relations	The ministry facilitates cooperation between the Netherlands and Aruba, in projects and policies that involve financial supervision, social development and infrastructure improvement. In the case of OTEC, it could help provide funding from the Netherlands.	Neutral
Ministry Climate and Energy Policy	Role: shaping and implementing the energy strategy and climate policies for the Kingdom of the Netherlands (incl. Aruba). Responsibilities include developing comprehensive plans to transition towards a more sustainable energy system. Has attended multiple energy transition conferences in Aruba/Caribbean.	Neutral
Subsidy Agencies		
International Subsidy Agencies (EU NER300 and Horizon Europe, NL SDE+ & DEI+)	Financing programs designed to support renewable energy projects. Programs can be focussed on the EU such as NER300 and Horizon Europe or more globally such as the Green Climate Fund (GCF).	Neutral

Figure D.3: List of of international governmental bodies stakeholders.

Society

Society

Stakeholder	Role/Description	Stance OTEC
Environmental NGO's		
Aruba Conservation Foundation (ACF)	Non-profit organization dedicated to the preservation and restoration of Aruba's natural environment, focussed on protecting local wildlife, preserving natural habitats and promoting sustainable practices. Can potentially interfere with RE project development plans (such as on shore wind turbines) due to ecological concerns.	Threat
Aruba Marine Mammal Foundation		Threat
Dutch Caribbean Nature Alliance (DCNA)	A regional network to enhance the conservation efforts in the Dutch Caribbean. It supports parks and protected areas by providing funding, resources and knowledge sharing to ensure effective management and preservation of natural environments.	Threat
Turtugaruba	Non-profit organization dedicated to the conservation of sea turtles and their habitats in Aruba. As OTEC would be placed in this habitat the potential impact of OTEC would have to be investigated.	Threat
Aruba Reef Care Foundation	Non-profit organization dedicated to preserving and restoring coral reefs and marine life around Aruba.	Threat
Sustainable Development Networking Organisations		
UNDP Aruba	UN's global development network, advocating for change and connecting countries to knowledge. Currently active in Aruba through funding/support of SISSTEM, the science faculty of Aruba's University. Supplying 7.3m euro funding through the 11th European Development Fund. Establishing the physical education facilities, hard (infrastructure) component of the SISSTEM programme.	Neutral
PAMEC Energy Association	Organisation that brings together researchers in marine technology in the America's (incl. Caribbean)	Pro OTEC
Rocky Mountain Institute (RMI): Island Energy Program	Initiative focused on transitioning island economies from fossil fuels to RE. Working with island governments and energy stakeholders, it implements bankable solutions for energy generation. Approach includes technical expertise, policy advocacy and project facilitation. The initiative is currently active in Aruba's wind and solar developments.	Neutral
IRENA: SIDS Lighthouse Initiative	Initiative from IRENA designed to support SIDS in their transition to renewable energy, which has been active in RE projects in Aruba in the past	Neutral
Climate Investment Fund	Set of international funding instruments to climate-resilient development through scaled-up financing.	Neutral
Energy Transition Accelerator Financing (ETAF)	Financial mechanism designed to expedite the transition from fossil fuels to renewable energy sources. Focused on providing large-scale financing solutions for projects reducing carbon emissions, such as RE installations.	Neutral
Dutch Marine Energy Centre (DMEC)	Provides consultancy services regarding ocean energy testing and networking.	Pro OTEC
Ocean Thermal Energy Association (OTEA)	Volunteer organisation providing a means for collection coordination, and dissemination of information on OTEC. Organises yearly conferences aimed at sharing and improving knowledge of OTEC.	Pro OTEC
CARICOM - CREEE	Found in (Link) Website	Pro OTEC
Clinton Climate Initiative	Program of the Clinton Foundation, designed to address the issue of climate change which has been active for RE projects in Aruba in the past.	Neutral
Media & End Consumer		
Media	Public opinion of subjects such as the Renewable Energy Transition and RE projects can be swayed by media coverage.	Neutral
Citizens / end consumers	The population on the island that requires electricity to operate their activities and businesses.	Neutral

Figure D.4: List of society stakeholders.

Knowledge Institutions

Knowledge Institutes

Stakeholder	Role/Description	Stance OTEC
Universities		
University of Aruba	Public university located in Oranjestad with a unit (SISSTEM) specialised on sustainable energy in SIDS.	Neutral
TU Delft	Public university in the Netherlands facilitating OTEC's development through research and collaboration with industry stakeholders.	Pro OTEC
Saga University, Japan	Public university in Japan researching OTEC with a small 100kW OTEC planted installed which is used for research, primarily focused on the heat exchange. Furthermore, they are investigating the use of deep-sea water in industry, for example in aqua and agriculture.	Pro OTEC
Universiti Teknologi Malaysia (UTM)	University located in Johor Bahru, Malaysia that has driven OTEC development through research and collaboration with other institutions through for example the SATREPS program. Additionally aided in the implementation of new regulation promoting OTEC development in Malaysia.	Pro OTEC
Research Institutes		
National Institute of Ocean Technology (NIOT)	Indian governmental agency developing technologies to harness ocean resources with a focus on OTEC, desalination, and ocean observation systems. Investigating a 1-5MW OTEC plant with Shell.	Pro OTEC
Hawaii Ocean Science and Technology Park (US Natural Energy Laboratory)	Facility administered by the Natural Energy Laboratory of Hawaii Authority (NELHA). Developing and demonstrating sustainable technologies using ocean resources. Currently hosts the world largest active 105kW OTEC plant.	Pro OTEC
Korea Research Institute of Ships & Ocean engineering (KRISO)	A government funded research institute in Republic of Korea with research into OTEC. Has been a front runner in developing and deploying OTEC, successfully deploying a 1MW OTEC plant in 2019.	Pro OTEC

Figure D.5: List of knowledge institutions stakeholders.

E

Influence matrix score: key stakeholders

To structure the placement of stakeholders in the influence matrix a scoring system is applied. The scores per stakeholder ranked from highest to lowest are described below.

Name of Stakeholder	Ability to Help	Ability to Hinder	Average
Government of Aruba	5	5	5.0
N.V. Elmar	4.5	4	4.3
WEB N.V.	4.5	3	3.8
Utilities Aruba	4	3.5	3.8
IPP	5	1	3.0
International Government	3	3	3.0
Technology Advisor	4.5	1	2.8
Financial Institution	4	1	2.5
Subsidy Agency	4	1	2.5
SD Network Organisations	3	2	2.5
Environmental NGOs	2	3	2.5
Knowledge Institution	3.5	1	2.3
Media	2	2	2.0
End Consumer	1.5	2	1.8

Table E.1: Stakeholder analysis scoring their ability to help and hinder.

F

Transmission and distribution loss comparison

The impact of different transmission and distribution loss factors (16%, 5%, and 20%) on installed capacities was analysed by adjusting the demand curve accordingly, with the results presented in Figure F.1. As expected, lower transmission losses result in lower required and installed capacities, while higher transmission losses lead to increased capacity requirements. OTEC remains present in all scenarios, with the technology shares remaining relatively consistent across the three cases. In the 20% transmission loss scenario, OTEC and wind slightly increase their shares as land-based solar reaches its capacity limit.

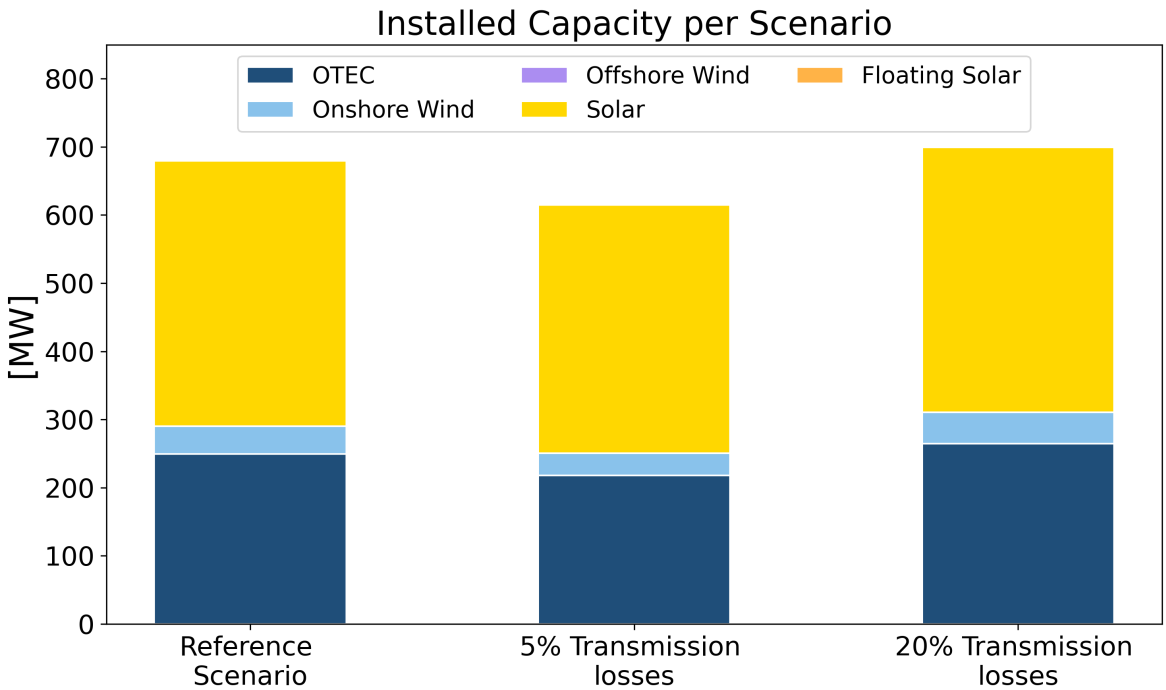

Figure F.1: Comparison of different transmission and distribution losses.