The Energy Potential of the Aruban Waters

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Aruba has been my home for a few years now.

When I came to my first day at the University of Aruba nearly three years ago I couldn't help but be reminded of the eight year old version of me. When she had just had her first diving lesson in the Caribbean sea, she had decided her dreams of becoming a mermaid had been accomplished and decided that from now on the dream was to do something good for the world on an island in the Caribbean. That little girl eventually had to go back home to a much colder Belgium, and would slowly start to forget her dream. I ended up graduating mid pandemic and feeling kind of lost with where the world was, until the University of Aruba, and with that SISSTEM suddenly popped into my view. I will always be grateful for John, who thought I might enjoy this new program that popped up on a small Caribbean island. I don't think he expected how seriously I would take his suggestion. SISSTEM indeed seemed perfect for me, and who better to convince me to make the big move than Eric Mijts. And just like that the little girl with a big dream was back and more excited than ever.

This project served as another reminder of that little girl and how proud she must be. Ever excited to learn something new, this course was another perfect fit. I was able to hear of so many more different experiences and perspectives. I loved seeing the differences in how all of us approached challenges and questions. As a STEM major you sometimes lose sight of the beauty of people, and for me this course served as a reminder of the beauty of our different perspectives. Seeing these students come in and fall in love with Aruba just as I did not too long ago is something I won't easily forget. Seeing how they see and feel passion for things that I never even noticed. How beautiful cultures can be nurtured and should be supported, how people are the drivers for change. I got to see how much I have yet to learn. And that little girl is once again excited to learn of more ways to make the world a better place. And she is even more excited to see how many others are already a positive influence wherever they go.

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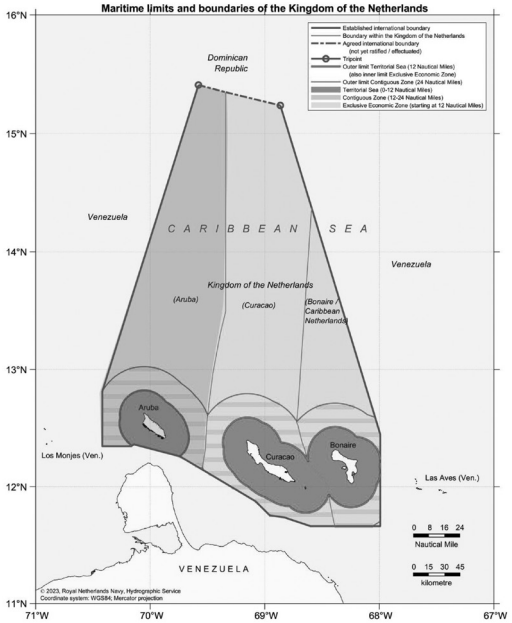
Introduction

Aruba, a small island developing state nestled in the southern Caribbean is now mostly known for its pristine beaches and dramatic rock formations. It has become a place many travel to every year to enjoy. A common challenge for small island communities in the Caribbean is the reliance on those tourists. The island has transformed to accommodate the large amounts of visitors, and as the years go by the island is almost unrecognizable for what it once was. Aruba was once one of the largest players when it came to the oil industry. So critical, in fact, that the Lago oil refinery in San Nicolas was specifically targeted during World War II by German submarines (Bongers, n.d.).

While Aruba's focus has long shifted to the tourism industry as opposed to oil based energy, the island still holds great potential to be a frontrunner among its kind. While usually "being an island" is regarded as a hardship, there is opportunity too, the blue economy. Defined by the World Bank as the "sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem" (PROBLUE: The World Bank's Blue Economy Program, n.d.) the blue economy has great potential for islands such as Aruba, where the ocean not only presents itself as a boundary, but also as a boundless source of renewable energy.

With an exclusive economic zone (EEZ) spanning 25 199 km2 (Marine Regions · Dutch Exclusive Economic Zone (Aruba) (EEZ), n.d.), over 130 times the area of the island itself, Aruba possesses a significant marine space relative to its own size that can be utilized for the diversification of the island's energy mix and possibly even its economy.



(Figure 1: modified from Royal Netherlands Navy, Hydrographic Service Coordinate system: WGS84. (2023). [Mercator projection of Aruba's EEZ])

This report aims to explore the energy potential of the Aruban waters, and to introduce and compare the different methods to capitalize upon this energy potential. The energy generation methods that will be explored and compared in this paper will be Floating Photovoltaics (FPV), offshore wind, wave energy, tidal energy, and Ocean Thermal Energy Conversion (OTEC).

Methodology

The preliminary research presented in this report is obtained through a broad review of existing literature. The selection of literature consists of research papers, reputable online sources, academic journals, government reports, industry publications, and scientific books. The literature review explores multiple aspects of marine energy technologies and their potential application in the Aruban context.

As a part of evaluating the applicability of marine energy technologies for the Aruban context, understanding the potential environmental impacts of these technologies is essential. A small island such as Aruba is in a vulnerable position when it comes to anthropogenic influences (Nature Today & Dutch Caribbean Nature Alliance, 2024). Aruba, in being currently dependent on the tourism industry, is also reliant on the marine environment to remain attractive for tourism. This marine environment can be kept attractive by being kept healthy, especially when it comes to the already vulnerable benthic species which include a wide range of marine flora and fauna (Eicher, 2023). An example of this existing vulnerability is the persisting issue of the stony coral tissue loss disease that has presented itself as a threat since an outbreak in December 2022 (Eicher, 2023). Environmental impacts are an important indicator to assist in deciding where or how a technology can be applied or if a technology is even suitable for the Aruban context.

To understand how the technologies discussed could contribute to Aruba's energy needs, it is also vital to discuss energy production estimates. This report will use these production estimates to compare the amount of space the various technologies need to produce enough energy to meet Aruba's present day average demand of 108 MW (WEB Aruba N.V., n.d.). When it comes to comparing the feasibility of use of marine energy technologies for the Aruban context the cost of energy remains one of the most prioritized factors. This report will use Levelized Cost of Energy (LCOE), a measure for the average cost per megawatt-hour (MWh) over the lifespan of an energy production facility, as a basis for economic comparison between the described technologies. All technologies will also be compared to Aruba's current average energy cost charged to consumers of 257.7$/MWh (Utilities Aruba & Elmar, n.d.).

As with any report reliant on a literature-based methodology, this report is subject to certain limitations. Some especially prominent limitations are the limited availability of region-specific studies, as well as language barriers that may restrict access to relevant sources. In particular, the scarcity of in-depth analyses that are focused on marine energy technologies in the socio-economic and geographical context of Aruba are a prominent limitation throughout this report.

Technologies

Solar Power

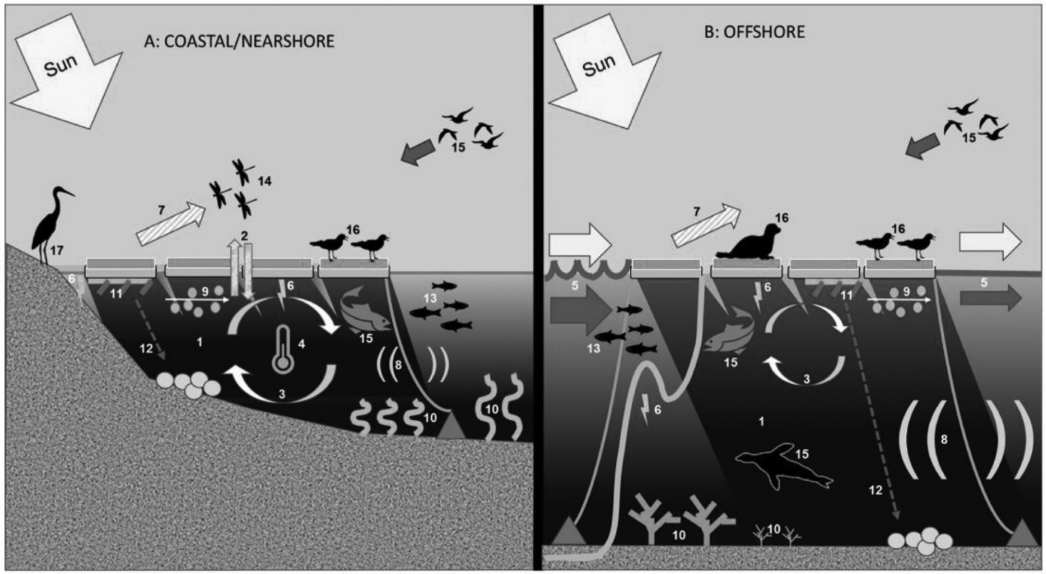
To generate energy using the potential of the ocean, firstly one could simply utilise the sheer amount of surface area available and harness the solar energy. This can be done by using floating arrays of solar panels that are anchored to the seafloor, and connected to land with transmission cables to transmit the energy they generate. One of the biggest limitations of solar energy is the need for large open spaces, something especially difficult for Small Island Developing States (SIDS) due to the limited terrestrial space available.

Using the surface area available on the water surface of Aruba's expansive EEZ instead can offer the opportunity to further capitalize upon the abundance of solar energy available in the region, using floating photovoltaics.

Floating solar installations, also known as floating photovoltaics (FPV), can greatly limit the solar irradiation, the floating structures usually don't let any or very little light through to the water below. While the impact of this limited irradiation would likely depend on the size of the installation, Benjamins et al. (2024) discuss that this shading can have negative impacts on organisms that are reliant on photosynthesis. Notable among affected species would be the group of benthic species, especially corals, that are already negatively affected in Aruba due to anthropogenic activity (Eicher, 2023). Benjamins et al. (2024) also clarify that the effect of this shading is far greater in shallow areas than in deeper waters where it is said to have very little effect on marine life.

Furthermore, these installations can influence hydrodynamics and water-atmosphere exchange. While in smaller scale freshwater installations it is a consideration that the systems reduce evaporation and the general exchange of gases between water and the atmosphere, in marine settings this is deemed as no concern due to the immense size discrepancy between the body of water and the surface area of the installation that would impact the gas exchange (Benjamins et al., 2024).

The mooring of the solar installations could also add to underwater anthropogenic noise pollution. The sounds created when anchor points are constructed as well as the sounds of the mooring lines once attached to the seafloor and the panels are hypothesised to be especially concerning in the case for larger offshore FPV installations in particular during weather events (Benjamins et al., 2024). This human-made underwater noise can affect marine animals that rely on sound for communication or navigation (Benjamins et al., 2024).



(figure 3: Benjamins et al. (2024). Schematic overview of the various potential impacts by FPV on the surrounding environment].

The estimated offshore photovoltaic capacity can vary between 10 and 15 MWp per square kilometre of installation area used (Ghosh, 2023), only 11 square kilometres would be needed to meet Aruba's average daily demand of 108 MW entirely by using floating photovoltaics.

Floating solar power is deemed one of the most affordable large scale marine energy solutions currently available. According to reported estimates, floating photovoltaics have an estimated production cost around 30$ per megawatt-hour for locations with solar incidence angles similar to Aruba (Ghosh, 2023).

Wind Power

Another popular method of generating renewable energy is the use of wind turbines to harness the kinetic energy of the wind. For Aruba, offshore wind energy holds great potential, especially due to its location in the path of the strong and constant Trade Winds. These Trade Winds make Aruba's northern coast a particularly attractive spot for offshore wind turbines. These turbines would usually be constructed using deep support structures anchored in the seabed and, just like FPV, connected to land using transmission cables. By constructing these turbines further offshore within Aruba's Exclusive Economic Zone, it is also possible to avoid common issues associated with land-based wind turbines such as concerns about aesthetics or noise pollution complaints.

Offshore wind farms can have significant environmental impact as, especially during construction, they can cause several environmental changes. The main initial pressures associated with the construction of wind farms are considered to be sediment dispersal as well as acoustic disturbances (Bergström et al., 2014). The construction activities such as drilling or pile-driving into the seabed can stir up sediment. This sediment dispersal will temporarily cloud the water, affecting nearby marine life, especially species that rely on clear water for feeding or breathing. Additionally, construction involves the use of heavy machinery, creating loud anthropogenic noise which again can impact marine animals relying on sound for communication or navigation (Benjamins et al., 2024).

Bergström et al. (2014) also describe how during the operational phase this acoustic disturbance continues, as well as other pressures such as electromagnetic fields, but also effects that they consider to be positive, such as fisheries exclusion, and habitat gain.

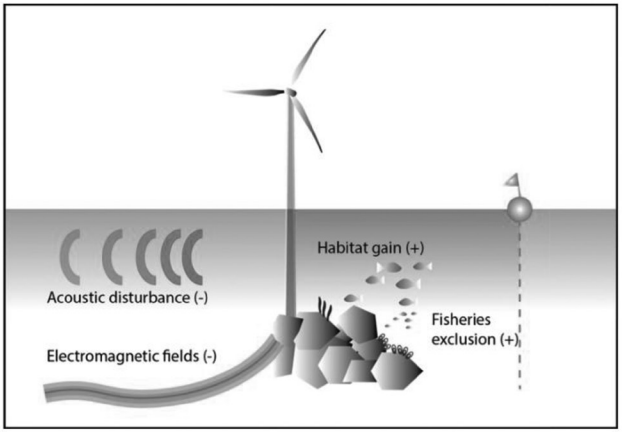


Figure 4: Overview of main pressures from OWF during the operational phase. Expected effect on the local abundance of marine organisms is indicated as (+) aggregation/increase, (−) avoidance/decrease (Bergström et al. 2014).

In figure 4 the positive and negative relationships of these effects are visualised. Gill et al. (2012) explain that while the shielded transmission cables, connecting the turbines to land to connect them to the grid, do not directly emit electromagnetic fields, they are surrounded by magnetic fields that in turn can induce electric fields in the water. When this does happen the electromagnetic field can impact and interfere with the orientation ability for migration as

well as their ability to detect prey or predator for certain fish. While Bergström et al. (2014) explain that generally the effects of the electromagnetic fields are deemed to be low, Gill et al. (2012) also indicate that negative effects can partly be mitigated by adjusting the cable design limiting the electromagnetic fields that are emitted. The acoustic disturbance however remains to have a far greater negative influence on marine life.

Current systems for offshore wind harnessing have a space efficiency of approximately 5 to 10 MW per square kilometre (Bulder et al., 2018). This implies that, similar to offshore solar power generation, an estimated 11 square kilometres would be needed to cover Aruba's own average demand using just offshore wind turbines (WEB Aruba N.V., n.d.).

While the LCOE of offshore wind energy has significantly decreased over recent years, its cost remains higher than that of floating photovoltaics. Offshore wind energy is estimated to have a global average levelized cost of energy of 95$/MWh (NREL et al., 2023). This cost could however still be lowered when the specific positioning and the trade winds are factored into estimations.

Wave Power

Wave energy can be much more effective generating the same amount of energy as a wind farms, using only 5% of the surface area (Slow Mill Sustainable Power BV, n.d.). The kinetic energy of the waves can be harnessed using novice technologies such as linear or point absorbers depicted in figure 2. These structures utilise the constant motion of the ocean waves, this movement holds a lot of kinetic energy especially in areas with constant waves. This makes wave energy an attractive solution considering the island's location in relation to the steady Trade Winds.

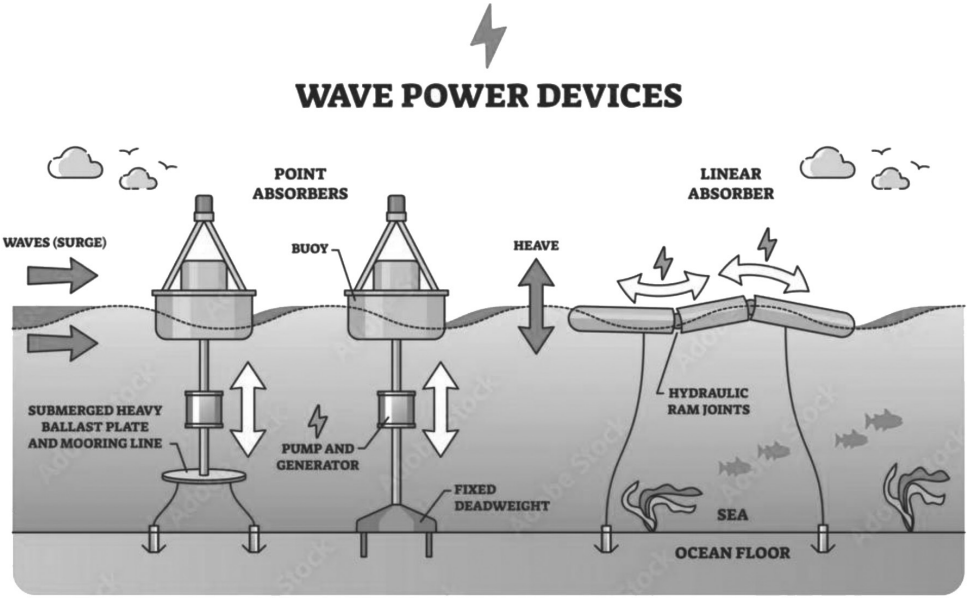


Figure 2: Wave power devices (Vector mine. n.d)

The point absorbers are floating devices that continuously bob up and down following the motion of the waves. As these devices move they drive a generator that converts this motion into electrical energy. Linear absorbers function similarly to the point absorbers while being longer articulated structures that follow the direction of the waves, thus capturing the energy along their length utilizing their hydraulic joints. Both methods would utilise a connection to last using transmission cables. This wave power is promising especially north of Aruba where most of our Exclusive Economic Zone is and where the waves action is stronger due to unsheltered ocean exposed to the trade winds.

The environmental impacts of wave power are largely similar to those of offshore solar power due to the similar ways the two technologies are anchored to the seafloor. While the seafloor disturbances of placing the mooring anchors are seen as temporary, the permanent mooring structures that remain are possibly impactful. That said, research by Akar and Akdoğan (2016) suggests that the impacts of these mooring anchors on the benthic communities are limited when assessed over the long term. A key difference between wave power devices and floating solar panels is that wave energy devices do not shield large areas from solar irradiation, thus having no shading effect.

Despite this, there are mentions of further potential concerns on underwater sounds created by the installation and operation of the wave converters that could interfere with the ability of marine animals to communicate and navigate (Copping et al., 2014). Lastly, similar to the other ocean-based energy systems discussed, the transmission cables used to transport the energy generated can produce electromagnetic fields, possibly impacting certain marine species.

While wave power generation is still in an experimental phase, Veerabhadrappa et al. (2022) show that for Aruba's conditions the potential energy in our waves is an estimated 20 kW/m of coastline. The EEZ area north of Aruba, being more exposed to the trade winds as well as less used for recreational tourism related activities can prove to be an area with great potential for future wave energy development. Though methods generating energy from waves are still relatively new, the technology still poses a promising future as innovation in the field accelerates. The technology still shows great potential currently as just 5.4 kilometers would be needed to meet Aruba's average demand of 108 MW (WEB Aruba N.V., n.d.).
Considering wave power is still a developing area, costs currently remain relatively high. The current levelized cost of energy of pilot projects for wave energy is around 360-690$/MWh(IRENA, 2014). These high costs make it a less attractive option for immediate investment, though continuing innovation in the sector shows future potential.

Tidal Power

Tidal energy attempts to harness the energy in the natural periodic rise and fall of the ocean's tides, which are caused by gravitational forces of the sun and moon (Shetty & Priyam, 2021). As this movement happens reliably every day, this presents to be a very predictable potential source of renewable energy. Historically people used tide mills, often built in the form of a barrage, to trap water at high tide and release it at low tide, turning water wheels to then generate power. However when it comes to the application for the Aruban context, constructing large barrages may not be a viable option due to the small difference between high and low tides in Aruba. Instead, a more practical and modern approach would be to use underwater turbines, similar to wind turbines in function, instead constructed on the seafloor connected to land using transmission cables. These turbines will spin as tidal currents flow past them, converting the kinetic energy of the moving water directly into electrical energy (Shields et al., 2010).

The environmental impacts of tidal technologies will largely depend on the scale and type of device used. While the more historically used tidal barrages can have significant ecological

effects due to their nature of trapping of water, these systems aren't likely suitable for use in the Aruban context. Instead, the turbines that are more likely to be used to harness the energy from tidal streams have a much smaller ecological impact, despite this there are still some environmental considerations. For example, the installation and operation of these turbines can cause disturbances to the seafloor, potentially affecting marine habitats, especially during construction (Shields et al., 2010). The research also indicates that the turbines might also pose a collision risk for marine life, though these effects need to be further investigated to accurately understand how large that risk collision is.

Technologies that harness the kinetic energy of tidal flows have estimated capacities of 5 - 10 MW per square kilometer (Shetty & Priyam, 2021). These capacities show similar promise to solar and wind power, and thus similar to those sources tidal power generation methods would need an estimated 10 to 11 square kilometers to satisfy Aruba's average energy demands (WEB Aruba N.V., n.d.). These estimated figures are based on average tidal flow speeds of 1 to 1.3 m/s the Caribbean region is considered a microtidal region with tidal flow speeds of 0.3 m/s (Expósito-Díaz et al., 2013).

Tidal power, similar to wave power, also remains in its experimental/development phase currently, and the field currently lacks research using the lower tidal flow speeds applicable to the Caribbean region. And its estimated Levelized cost of energy at 380$/MWh makes it a currently less profitable energy generation method to invest in (Bianchi et al., 2024). Based on this, presently, the application of both tidal energy and wave energy are deemed unfeasible in the case of Aruba, unless the application serves the purpose of further advancing the development of these technologies.

Ocean Thermal Energy Conversion

Ocean Thermal Energy Conversion (OTEC) can serve as a less space intensive marine energy source that takes advantage of the temperature difference between the warmer surface water and colder deep seawater to generate energy (IRENA, 2014). The technology works by pumping up cold water from deep levels of the ocean through large pipes and combining it with warm surface water. This warm surface water is used to evaporate a working fluid, the vapor is passed through a turbine to generate electrical energy. Hereafter the vapor is condensed into liquid again using the colder deep ocean water. Generally needing a temperature difference of 20^0C to function, the Caribbean serves as an ideal region to utilize this energy generation method. In addition to this OTEC has a multifunctionality in addition to generating electricity the cool seawater could also be used to assist in air conditioning systems. Furthermore fresh water is a byproduct of OTEC power production, this can be used to support the water production in Aruba, seeing the island already relies on desalination for its drinking water (IRENA, 2014).

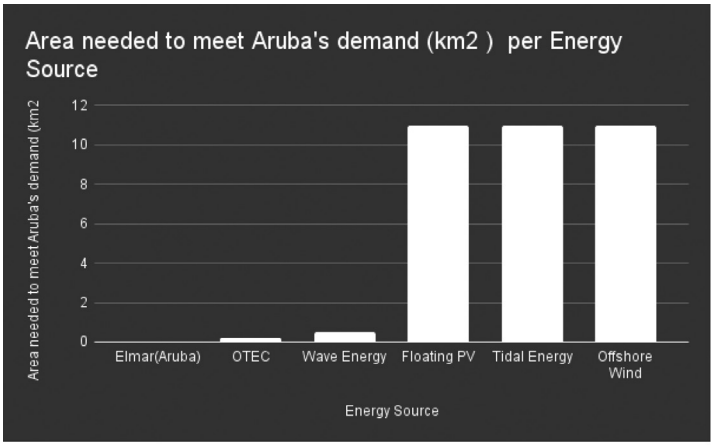
Ocean Thermal Energy Conversion (OTEC) generally has a low environmental impact. The main environmental concern is the potential electromagnetic interference from the transmission cables, though this effect can be minimized by the strategic selection of the location of the plant. Despite its low impact, further research is needed to fully understand the environmental effects of OTEC. For example, NOAA notes that these installations may disrupt the water column as the nutrient-rich water discharged by these systems can affect local marine ecosystems, especially in areas where the surface water is naturally oligotrophic (low in nutrients) (NOAA, n.d.).

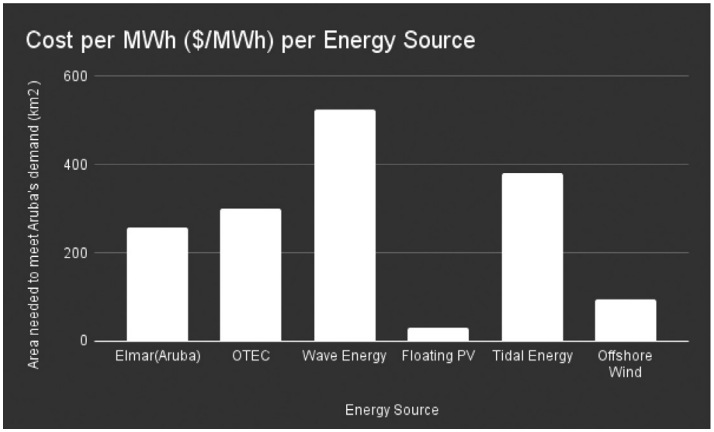
One OTEC plant can have a capacity of between 10 and 100 MW, depending on its design and infrastructure (IRENA, 2014). To meet Aruba's average energy demands fully, a larger scale OTEC plant would be needed matching Aruba's energy demand of 108MW (WEB Aruba N.V., n.d.). Currently no active OTEC plants approach this size as currently much smaller plants are used as pilot projects

to valorize the technology. Using a proposed OTEC plant in Indonesia with a capacity of 100 MW as an example, a required area of 0.01 to 0.02 square kilometres can be found (Adiputra et al., 2019). With a current LCOE of around 300$/MWh this energy generation method can be specifically interesting for island states that often have similar high energy rates already (IRENA, 2014). This cost can be lowered however when using the OTEC as a combination of energy generation and drinkable water purification as well as utilizing larger scale plants. OTEC can be used as a desalination technique resulting in a lowered cost for both water generation as well as energy generation (IRENA, 2014).

Discussion

Comparing Aruba's current average energy cost of 257.7$/MWh (464.5 Afl) as well as Aruba's average demand of 108MW shows interesting comparisons (Utilities Aruba & Elmar, n.d.).





(figure 5: [Marine area needed to meet Aruba's demand per energy source]) (figure 6: [cost per megawatt-hour per energy source])

Comparing these criteria using figure 5 and figure 6 that visualize the data it becomes clear that no single technology dominates greatly when comparing cost and productivity in this context.

From an ecological perspective, wave power, floating photovoltaics, and OTEC tend to be the least environmentally disruptive. It is notable that in the case of OTEC it is made very clear that there is a current lack of data concerning the environmental impacts especially in regards to the discharges. The shading risks of the floating photovoltaics, while impactful, are not a concern when installations are placed further offshore.

In terms of energy generation potential, all discussed energy generation methods are capable of far exceeding Aruba's average energy demands, though the technologies vary significantly in space efficiency. OTEC and wave power stand out as the most space efficient while floating photovoltaics, tidal power, and offshore wind power all require similar area's for reaching Aruba's average demand.

When comparing the LCOE with the other technologies, a different trend emerges. One where floating photovoltaics and offshore wind power stand out greatly as more affordable energy generation methods even compared to the current cost of energy using fossil fuels. While the more experimental energy generation methods remain at higher costs for now it is seen that with more development and future economies of scale these will possibly become more promising solutions.

One energy generation technology does emerge as having more utility than solely generating power, Ocean Thermal Energy Conversion. With the added utility of the byproducts produced, while producing power, this technology appears to be more cost effective than initial estimates show. The integration of energy production with fresh water production and seawater air conditioning, holds great energy savings potential.

Conclusion

This literature review mostly focuses on the practicalities, i.e. the economic interests, of the energy generation potential within the Aruban waters. There are of course many more aspects to be considered. Some of these aspects are import logistics, longevity, maintenance, used materials, carbon footprint, and overall sustainability of the energy generation methods. However, looking at the findings in this literature review, it already becomes clear that Aruba can greatly benefit from investing in ocean-based energy generation techniques. And even when using the least space efficient methods, using less than 0.5% of the Aruban EEZ is required to generate over 10 times the average Aruban demand. The most promising technologies for Aruba appear to be floating photovoltaics, offshore wind power, and OTEC. The documentation on OTEC lacks information, the information that is available shows great potential specifically for the application in SIDS.

Further research will continue to build upon this literature review with more specific data and calculations further examining the import logistics, longevity, maintenance, used materials, carbon footprint, ecological impacts, social acceptance and overall sustainability for the region and Aruba specifically. These calculations will involve more data specific to the Caribbean region as many reports used in this literature review were based on information relevant to different regions, which might lead to inaccurate estimations. An accurate comparison of alternative marine based energy solutions for Aruba will be developed. This with the goal of making realistic predictions and recommendations for Aruba to invest in marine energy.

Aruba has the potential to become a large player in the energy sector again and gain a level of independence from its tourism sector. Aruba could take advantage of its boundary of boundless ocean energy. The island could invest in the blue economy and marine energy to first harness accessible

and affordable energy for its own people, before potentially even becoming a provider for other nearby territories. This could lead to a degree of independence from the tourism industry and to the diversification of Aruba's economy, creating more security for the island and its people.

There is great potential to be found in the deep blue. All we need to do is reach out to it.

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