2024

# GIS-based Multi-Criteria Decision Analysis for Marine Energy Site Selection: A Case Study Comparison between Puerto Rico and Hawaii

Sarah Hall

# GIS-based Multi-Criteria Decision Analysis for Marine Energy Site Selection: A Case Study Comparison between Puerto Rico and Hawaii

An Honors Thesis Presented by:
Sarah Hall
To the Environmental Studies Program

An honors thesis submitted in fulfillment of the requirements for the degree of Bachelor of Arts in Environmental Studies
Connecticut College
New London, CT

Thesis Committee:
Advisor: Douglas M. Thompson, Ph.D., Advisor and Committee Chair, Departments of Physics, Astronomy and Geophysics, and Environmental Studies Program, Connecticut College

Reader: Beverly Chomiak, Ph.D., Departments of Physics, Astronomy and Geophysics, and Environmental Studies Program, Connecticut College

Reader: Katie Peterson, Ph.D., Water Power Research and Development Team, National Renewable Energy Lab

Senior Honors Thesis: Environmental Studies

# GIS-based Multi-Criteria Decision Analysis for Marine Energy Site Selection: A Case Study Comparison between Puerto Rico and Hawaii

Sarah Hall (2024)

## Abstract

Geospatial information systems (GIS) enable easy visualization of geospatial data representing different criteria important for optimal siting of marine energy projects. Multi-Criteria Decision Analysis (MCDA) is a geospatial analysis method that facilitates the evaluation of multiple, usually overlapping, site criteria. While GIS-based MCDA has been used extensively for land-based renewable energy projects, limited research exists on its application to marine-based renewable energy projects. Similarly, most literature overlooks the integration of social or environmental justice data. This project applies GIS-based MCDA to conduct site selection analysis for two marine renewable energy (MRE) projects in Puerto Rico and Hawaii. The results for Puerto Rico indicate that Coastal Structure Integrated Wave Energy Converter (CSI-WEC) projects should be focused primarily along the main island, specifically the northeastern and southern coasts. Similarly, the study in Hawaii demonstrates the feasibility of a hybrid wind-wave-solar project near the islands, particularly off of the northern coasts. The inclusion of social justice data yielded different site selection outcomes compared to analyses considering solely technical and resource criteria, suggesting the importance of incorporating social data into future site selection decisions. Between study sites, variations in the results were observed based on the criteria chosen and their respective weightings. Both studies' results indicate the suitability of GIS-based MCDA methodologies across diverse locations and MRE technologies.

## Acknowledgments

Throughout this process, I have been incredibly fortunate to receive support from numerous individuals.

Firstly, I extend my deepest gratitude to Dr. Doug Thompson for his unwavering guidance and mentorship during my time at Connecticut College and throughout the process of crafting this thesis. Doug's first-year seminar ignited my interest in the environmental sciences, and his continued support has been instrumental in shaping my academic journey. His insights and dedication as my thesis advisor have played a pivotal role in my growth and accomplishments.

I would also like to thank Dr. Beverly Chomiak for her invaluable contribution as a second reader, providing insightful feedback and thorough edits that greatly enriched the quality of this work.

Further recognition goes to the faculty, staff, and students in the Goodwin-Niering Center for the Environment. The center has provided me with the opportunity to write this thesis but also enriched my academic experience at Connecticut College.

Special recognition is extended to my mentor at NREL, Dr. Katie Peterson, whose guidance and support during my SULI internship this summer and throughout this entire year have been invaluable. I am also grateful to Dr. Ben McGilton, David Greene, and Kelly Gjestvang from the CSI-WEC team for their support during my summer SULI appointment and for introducing me to key topics that have significantly influenced my thesis.

Finally, to my family, I offer my heartfelt thanks for their unwavering encouragement and support throughout my entire academic career. Their support has been a constant source of strength and motivation.

# Table of Contents

# 1 Introduction

With the increasing threat of climate change, the need for climate action is immediate (IPCC, 2023). The global average surface temperature from 2011 to 2020 was 1.1°C warmer than 1850-1900 (IPCC, 2023). Human-induced fossil fuel combustion is the greatest source of this rise. The United Nations Intergovernmental Panel on Climate Change (IPCC) has released reports showing that in order to limit the severity of future climate change impacts, global emissions must be immediately and drastically reduced (IPCC, 2023). Therefore, there is a particular emphasis on the transition from fossil fuels to renewable energy. Many countries have set goals for renewable energy transition, for example, the United States has set a 2035 goal to reach 100% carbon-free electricity generation and a 2050 goal to reach a net zero emission economy (Fact Sheet, 2021). However, in 2022, only 21.5% of electricity was generated from renewable energy sources (U.S. Energy Information Administration [EIA], 2023a). In order to meet this ambitious 2035 goal, the U.S. needs to utilize a wide range of energy sources, such as the ocean which has immense energy extraction potential. However, it should be acknowledged that all resources are finite, and the impacts of over-extraction should be heavily considered. Marine renewable energy (MRE) includes energy produced by ocean waves, currents, tides, changes in temperatures, and offshore wind (Caballero et al., 2023). There are many promising technologies in the marine energy industry that range from wave energy converters to tidal energy converters. Ocean wave, thermal, tidal, and riverine technology could provide an estimated 57% of U.S. energy generation (Kilcher et al., 2021b). However, not all locations are equally suitable for every energy device. In the past, the different variables that influence a site's suitability have only been connected to energy extraction potential, such as measurements of solar energy power potential. The current system for site selection in MRE is inadequate due to the exclusion of other valuable criteria. Many methods now allow for the inclusion of a broader range of criteria, such as environmental, social, and economic data. This paper will explore a different method of site selection in the context of the MRE industry that incorporates not only energy resource data, but also technical, socioeconomic, and environmental data. In site selection decisions, the inclusion of social justice factors creates better results than analysis with just technical factors and facilitates more equitable siting decisions. Results from the site suitability analysis illustrate the advantages of deploying Coastal Structure Integrated Wave Energy Converters (CSI-WEC) sites in Puerto Rico and Hybrid-Wind-Wave-Solar in Hawai‘i.

Social and environmental justice movements have spurred important discourse around the impact of energy systems indirectly and directly on communities. There is an increasing need for the renewable energy transition to be sustainable and equitable. The MRE industry is still in the beginning stages. Therefore, there is an opportunity to incorporate sustainable and equitable practices into every MRE project. During a project’s timeline, site selection is the critical time when environmental justice frameworks can characterize the impact of a project.

One of the primary tools that allows for this type of intersecting analysis is Geographic Information Systems (GIS), which is computer software that allows for the visualization and manipulation of geospatial data. Multi-Criteria Decision Analysis (MCDA) is a method of analysis that allows for the integration of multiple factors (criteria) into a decision (Mueller & Wallace, 2008). Combining GIS and MCDA allows for the analysis of various data sets that have geospatial components important to a site selection decision. GIS MCDA has been used extensively in Europe for onshore solar and wind projects to help identify locations with greater energy resources and less social impact (Ali et al., 2020; Peters et al., 2020). However, it has yet to be used extensively for marine energy projects.

The two locations selected for analysis in this study were Puerto Rico and Hawaiʻi. Puerto Rico was selected because it is in a region highly susceptible to natural disasters, specifically hurricanes. Past hurricanes have devastated the island and disrupted energy access for long periods (Houser and Marsters, 2017). Climate change brings the threat of increasing intensity and frequency of hurricanes (Puerto Rico Climate Change Council [PRCC], 2013). Puerto Rico has set ambitious renewable energy goals in order to increase energy independence and resiliency (Blair et al., 2023). Puerto Rico has a rich marine energy resource potential, particularly on the north shore, thus there are many potential sites for different energy devices. However, there is a history of corruption and underinvestment resulting in worsened conditions for Puerto Rican citizens (Pietri, 2017). Therefore, it is important to include socioeconomic data in order to highlight areas that have been historically underserved. Hawaiʻi was selected as a comparison island site. Hawaiʻi also has a strong marine energy resource. There are many opportunities for both wave, wind, and offshore solar. Furthermore, Hawaiʻi is one of the most petroleum-dependent states in the U.S. and has some of the highest energy costs in the country (EIA, 2023b). Marine energy projects could help diversify Hawaiʻi's energy portfolio and reduce energy costs long-term. Both case studies highlight different communities, different energy technologies, and use varying data sets.

The objective of this project is to use GIS-based MCDA to conduct site selection analysis in the MRE industry. GIS MCDA methods are reviewed and then applied to two case studies for different marine energy applications in isolated island sites. For each study area, four final maps were created: a resource overlay, a resource and technical overlay, and a complete overlay including social and environmental data. These were analyzed to explore the differences in site suitability results that occur with the inclusion or exclusion of different types of data. For example, the inclusion of social justice data might prioritize cities without well-developed energy infrastructure, which otherwise might be classified as less desirable. This project demonstrates an application of GIS-based MCDA methods for MRE site selection through the comparison of two different study areas, and specifically highlights the importance of incorporating social and environmental justice data into site selection decisions.

# 2 Literature Review

The literature review covers the siting considerations of different renewable energy resources, environmental justice in renewable energy, Marine Spatial Planning (MSP), and GIS based MCDA methods. In total, over 50 papers were reviewed, and the majority of papers reviewed focused on GIS and MCDA methods. The two main review papers on GIS and MCDA for renewable energy site selection analyzed literature ranging from 2001 to 2022 (Hosseinzadeh et al., 2023; Shao et al., 2020). Most marine energy focused papers were published after 2018. Literature on GIS-based MCDA for land-based renewable energy projects is well established, but there are knowledge gaps in the application to marine energy.

## 2.1 Siting Requirements

The first step of any new energy project is site selection for optimal power production. This process can be very complex as there are many requirements to consider. Some criteria are essential for all projects, such as the energy resource available and the amount of surface area required. However, many more criteria are resource specific. These are further explored below.

### *2.1.1 Photovoltaic*

Photovoltaic (solar) projects have minimum solar irradiance and number of sun-hours requirements that generally drive site selection (Deveci et al., 2021). Lower latitudes, locations closer to the equator, receive higher amounts of solar insolation than higher latitudes because of the angle that the sun's rays strike the earth. The orientation of solar panels with respect to the sun's rays is critical to maximizing energy production. The specific orientation varies based on location; for example, solar panels need to be mounted at a steeper angle in higher latitudes.

Moreover, topography is also influential, as hills or slopes can change the orientation of the rays received by the devices and make construction and maintenance access more difficult (Janke, 2010). Another condition is the average air temperature, which impacts the efficiency of the device (Deveci et al., 2021). Additionally, areas at risk of flooding or high amounts of rain are less desirable. Landcover and surrounding vegetation must also be considered, as shading from large trees can also impact the amount of solar insolation received (Janke, 2010). The proximity to an electric grid connection is necessary for calculating the transmission cost, as locations closer to a community or electric grid connection are often more cost-effective.

A significant environmental concern associated with solar projects is that they occupy large amounts of surface area (Hall et al., 2022); thus, the location of critical habitats and endangered species must be avoided when selecting project sites. Some solar arrays, especially large commercial ones, can create a visual impact as light is reflected off the solar panel surfaces. However, not all panel designs create this problem, thus, the panel design type determines if this effect should be considered.

### *2.1.2 Wind*

Onshore and offshore wind projects generally have similar technical requirements; for example, wind speed at the specific hub height directly determines energy production potential (Bashir, 2022). In 2022, the average hub height of onshore commercial wind turbines was 98 meters (roughly 322 feet) (Hartman, 2023). Wind speeds generally increase with height above the ground as the effect of surface friction decreases. This principle is called wind shear, and it also plays a role in the arrangement of wind turbines (Murphy et al., 2020). Friction and turbulence caused by wind passing through turbine blades reduce the wind speed, thus the arrangement of the wind farms must minimize interference of the upwind turbines (Miller & Kleidon, 2016). The maximum wind speeds and seasonal variation in wind dictate the speeds that the turbines must be able to withstand (Moradi et al., 2020). Distance from communities and grid connections with sufficient electrical capacity is an essential factor for transmission lines and grid integration (Moradi et al., 2020).

Some specific variables primarily linked to ocean conditions are important for offshore turbines. The ocean depth and bathymetry dictate the type of moorings the device will use, which is the method of attachment for a device to the sea floor (Flocard et al., 2016; Kaldellis et al., 2016). Also relevant is the distance to shore, which impacts the site accessibility for construction and maintenance activities (Bashir, 2022; Kaldellis et al., 2016). The maximum wave height dictates the structure design and ability to withstand impact from waves (Hosseinzadeh et al., 2023). Additionally, the frequency and intensity of storms must be assessed to avoid high-risk locations. Hurricanes are a specific concern for the U.S. in the Atlantic Ocean, especially higher-category storms. However, due to the unpredictability of most hurricanes, it is hard to factor them into site selection; instead, it is important for design mitigation strategies to be implemented (Jaramillo, 2012).

Wind turbines can have unwanted impacts on the surrounding environment. There is evidence that turbines impact aerial species such as bats and birds (Saidur, 2011). The impact is minimal relative to other human activities that harm bird populations, and some precautions can be taken to mitigate impacts on species (Kaldellis et al., 2016; Sovacool, 2009). However, this is important to consider, and areas with endangered or sensitive species should be avoided, such as highly populated breeding grounds or migration paths. Similar to solar arrays, a significant impact of wind farms is the associated surface area use, which can destroy critical habitats.

Offshore wind farms have the potential to further impact the environment, particularly sensitive marine ecosystems. The moorings and cables below the surface can impact surrounding fish and marine mammals (Bashir et al., 2022). Siting decisions should also consider the location of critical coastal habitats, migration patterns, and nesting sites of marine wildlife. Additionally, use conflicts become more complicated in the marine space, with boat traffic and commercial fishing communities also competing for use (Bashir et al., 2022). High-density shipping routes should be avoided for wind turbine sites, along with essential fishing grounds.

Wind farms can also pose a threat to the living and cultural landscape. In the event of a malfunction, the turbine blades or any other parts are very dangerous, which applies to marine and terrestrial spaces (Abbasi, 2000). During low temperatures, a phenomenon known as ‘ice throw’ can occur where ice that has built up on turbine blades falls while operating. While not common, sometimes the ice can travel a significant distance from the structure (Preziuso & Orrell, 2022). It should be noted that ice throw is a minimal hazard associated with offshore wind turbines. A buffer zone should be established for the safety of lives and infrastructure; thus, this space must also be accounted for during the siting process. Another impact to consider is the shadow flicker effect, where the sun at a low angle on the horizon can cast a moving shadow of the turbine blades, which creates the visual of a flickering light (Office of Energy Efficiency and Renewable Energy [EERE], n.d.). The flicker effect can affect nearby communities; however, it is a greater problem at higher latitudes where the sun is often at a lower angle (EERE, n.d.). This hazard should be included in siting decisions for locations at high latitudes with conditions conducive to the flicker effect. Noise pollution can be a factor as well. Noise from moving turbines and structure machinery can cause disturbances to nearby communities; however, there is little conclusive research on the direct impact on people (Leung, 2012). Turbine design can be adjusted to lessen the noise level, and siting wind farms at a distance from communities may be something to consider. Finally, the visual impact of the turbines can be very controversial (Kaldellis et al., 2016; Leung & Yang, 2012). Many communities have complained that the turbines are ‘eye sores’ (Smith & Klick, 2008); however, wind farms have increased tourism or become sources of community pride in other locations. For example, researchers saw increased tourism in the summer months after a wind farm was built off the coast of Block Island in Rhode Island, U.S. (Carr-Harris & Lang, 2019). The response to the visual impact of wind farms is very community-specific and necessitates engagement with local stakeholders through the siting process.

### *2.1.3 Wave*

A standard wave energy converter (WEC) device design has yet to be established in the wave energy industry; consequently, it can be hard to determine general site requirements. The specific oceanographic requirements can vary from device to device, especially the required depth and wave energy extraction potential (Flocard et al., 2016; Hosseinzadeh et al., 2023). Significant wave height, wave direction, and wave period are necessary data used to estimate total wave energy resource and predicted power production from a WEC (Flocard et al., 2016). The seasonal wave variability is used to predict power production variability, and the peak wave height dictates the extreme conditions a device must endure (Flocard et al., 2016). Additionally, the distance to shore affects accessibility for installation and maintenance, and subsequent operations and management costs (Flocard et al., 2016; Kamranzad and Hadadpour, 2020). The further from shore a device is, the more challenging transmission and grid connection becomes. Bathymetry is also necessary to consider as it impacts the strategy used for transmission, such as if seafloor cables are feasible (Flocard et al., 2016; Hosseinzadeh et al., 2023). Depending on the device's design, bathymetry also influences mooring.

WECs have the potential to impact the marine ecosystem, though many of the impacts are not fully understood (Mendoza et al., 2019). Electromagnetic fields associated with wave energy equipment can interfere with the activities of marine mammals and fish, specifically breeding and eating habits (Hildenbrand, 2014). Many biological functions of marine species rely on sounds, such as communication, orientation, and hunting. The noise generated by wave energy devices, during operation and installation, are potential stressors for nearby marine species (Polagye and Bassett, 2020). Although, some studies have found that the noise generated does not exceed surrounding ambience noise, thus it is unlikely to cause harm to marine animals (Polagye and Bassett, 2020). Overall, areas with critical habitats and endangered or protected species should be avoided during site selection (Hosseinzadeh et al., 2023).

Similar to offshore wind, there is potential for conflict with other marine activities. Navigation is restricted in areas where there are WECs, which could create conflicts with commercial or recreational fishing, boat traffic, and shipping routes (Hosseinzadeh et al., 2023). In order to address potential use conflicts, it is important to avoid high-traffic areas and to include local stakeholders once locations are selected.

## 2.2 Marine Renewable Energy Projects

### *2.2.1 CSI-WECs*

The sea level along the U.S. coastline is expected to rise 10-12 inches (0.254-0.3 meters) on average over the next 30 years due to anthropogenic climate change (Sweet et al., 2022).

Furthermore, as storms increase in frequency and intensity, coastal communities will be at greater risk of flooding from storm surges, which is an increase in sea levels past normal levels due to a storm's low pressure and high winds. Coastal-protection structures, such as breakwaters and seawalls, are often used to mitigate the impact of coastal storms. Seawalls are structures built into shorelines to protect structures onshore from flooding and erosion. Breakwaters are often a short distance offshore and parallel to the shoreline; they are constructed to reduce the force of waves on the shoreline. Currently, 14% of the U.S. shoreline is hardened with protective structures, which is predicted to increase to protect against the impacts of climate change (Gittman et al., 2015). Coastal defense structures are effective against storms but have high construction and maintenance costs (Hinkel et al., 2014). A major environmental concern of defense structures is the increased erosion of shores located next to the structures (Gittman et al., 2015). One strategy to reduce lifetime costs is to integrate wave energy converters into existing or planned defense structures. The protective function of coastal structures remains the primary purpose of CSI-WECs, and some models have shown increased hydraulic performance in comparison to typical structures (Vicinanza et al., 2019; Viviano et al., 2016). This includes a reduction of wave reflection from the devices as the WEC absorbs more wave energy, which should decrease down shore erosion (Vicinanza et al., 2019). Furthermore, CSI-WECs can function as non-grid-connected devices, where they are not connected to the larger utility-scale grid but instead directly power some local activity. For example, they can serve as an emergency backup generator after storms, power desalination for drinking water, or power local port operations.

The site selection of wave energy converters (WECs) generally focuses on maximizing potential power generated from the local wave energy resource, with constraints dictated by extreme sea states. Unlike WECs, CSI-WECs are located on or near shore, thus, they often operate at lower wave energies. As a result, the local energy resource is less critical during site selection. However, other criteria are important to consider during site selection for CSI-WEC projects. For example, information on existing breakwater structures helps identify opportunities where wave energy converters can be integrated into existing structures. Additionally, socioeconomic data such as “energy-disadvantaged” communities that have high energy costs and unreliable energy access, is also essential to facilitate the siting of projects in areas that have been historically underserved or burdened. Finally, climate projection data like sea-level rise data helps identify communities most vulnerable to storms and needing shoreline protection structures. A compilation of this data is very important for guiding CSI-WEC site selection.

There are other locations that are often considered compatible for CSI-WEC sites. For example, ports and marinas usually have existing breakwater structures, and port operations can be powered by CSI-WECs. Some CSI-WEC devices have been designed to emulate reef structures to support marine growth. This is particularly helpful in coastal ecosystems where the reef has been degraded. Finally, coastal industry sites (wastewater treatment, electrical power plants, oil rigs) can also benefit from the protection and energy provided by CSI-WECs.

### *2.2.2 Hybrid Energy Systems*

A hybrid energy system typically involves a combination of multiple energy sources or energy storage devices or both (Department of Energy [DOE], 2021). Hybrid energy systems can reduce the costs and deployment of emerging energy technologies by pairing newer energy devices, which have higher risks and costs, with more established energy technologies (DOE, 2021). This project will explore a complementary offshore wind, offshore floating solar, and wave hybrid system. Conventional solar and wind farms have continued to grow in the percentage of total energy production for the U.S., but the intermittency of these energy sources continues to create challenges for continued growth. However, the collocation of wind and solar energy systems with other emerging energy systems, such as wave energy, can allow for increased grid reliability (DOE, 2021). All renewable energy resources have their own unique temporal and seasonal variability, which depends on location. For example, generally, solar energy production is higher in the summer, whereas wind energy production peaks in spring to early summer (DOE, 2021). Therefore, wave energy can fill gaps in coverage as it peaks in the winter months *(*Gideon & Bou-Zeid, 2021). The benefits of hybrid systems include decreased power variability, increased energy yields, and reduced costs due to shared maintenance and transmission costs (Gideon & Bou-Zeid, 2021).

A general optimized hybrid configuration does not exist, as this is highly dependent on local energy resources and energy infrastructure (DOE, 2021). Therefore, the site selection process is particularly important for guiding the system planning (DOE, 2021). Generally, hybrid wind-wave-solar projects are located where all three resources are abundant. Therefore, criteria such as wind speed, wind direction, wave energy, solar insolation, and temperature are all important. Furthermore, energy infrastructure data such as electric transmission line locations and port locations are important for integrating the project into the existing energy grid, which dictates costs. A hybrid wind-wave-solar project is usually located offshore in the marine space, which creates the potential for conflict with other activities in the marine space. Data can be included to limit overlap with critical marine activities, such as popular shipping routes and critical fishing habitat.

## 2.3 Social and Environmental Justice Factors

Beyond the technical, economic, and environmental factors that influence siting decisions, it is also imperative to include social and environmental justice data. Environmental justice is a movement that started in the late 1980s to protest the placement of pollution sources near communities of color (Mohai et al., 2009). The field has continued to grow and expand to encompass a wider definition. The Department of Energy (DOE) defines environmental justice as the “just treatment and meaningful involvement of all people” regardless of race or socioeconomic status in order to ensure that low-income communities are not disproportionately burdened by environmental hazards or risks, nor deprived of access to a healthy environment in which to live (Office of Legacy Management, n.d.).

Historically, energy projects (coal, oil, gas) have been placed in socially vulnerable communities, subjecting these communities to adverse impacts such as increased air pollution and exposure to toxic chemicals (Kyne & Bolin, 2016; Outka, 2012). Furthermore, many communities have been physically displaced by energy projects or their livelihoods have been significantly impacted. For example, one U.S. study estimated that over 1.13 million acres of tribal land were flooded by reservoirs to form roughly 500 dams for hydroelectric power generation (Randell & Curley, 2023). Many indigenous groups in the Pacific Northwest see salmon fishing as an essential part of their livelihoods, not only as a food source but as a part of religious and cultural practices (Earth Economics, 2021; McGill, 2016). The construction of dams has drastically reduced salmon populations and destroyed many traditional indigenous fishing spots (McGill, 2016; Randell & Curley, 2023). Finally, the cost of energy is disproportionately higher for low-income and minority communities. Studies have found that the majority of low-income and minority households in major U.S. cities faced higher energy costs in comparison to higher-income households in the same city (Drehobl et al., 2020; Jessel et al., 2019).

As our society looks to transition to clean energy and there is an increase in renewable energy projects, siting decisions must be made differently. There is a clear link between social impacts and siting decisions, but researchers have found that very few energy projects incorporate human dimensions into project development (Caballero et al., 2023). Social and environmental justice data, in addition to technical and environmental factors, must be considered. This will allow for the inclusion of communities that have historically been disproportionately burdened by energy projects or overlooked by the clean energy transition. Potential community benefits include reduced energy costs and less exposure to public health hazards from other energy sources. Furthermore, these marginalized communities are now facing the highest risk from climate change; therefore, integrating social data increases community resiliency by prioritizing projects in these high-risk communities (Outka, 2012).

Including social data also encourages local engagement and representation, which is needed to move forward with equitable energy projects. In many communities that have faced oppression, there is deep-rooted mistrust in local government bodies. This results from a lack of representation and exclusion of community members in decision-making (Carmichael & McDonough, 2019; Lee & Byrne, 2019). Consideration of social data and inclusion of local stakeholders allow conflicts to be addressed earlier and with greater transparency, facilitating trust. For example, the Igiugig community in Alaska is a remote community in southwestern Alaska located along the Kvichak River. The river is essential to the community as a water source and habitat for salmon. The community relies mainly on imported diesel for energy production, which is incredibly expensive and sometimes unreliable. The community created a plan to transition to a more sustainable energy source and, in partnership with the National Renewable Energy Lab (NREL), explored renewable options for the Kvichak River (Kilcher et al., 2021a). However, because of the importance of salmon to the community, it was critical for the device installed to have little to no impact on the salmon population. Through the partnership with NREL, a successful riverine energy device that provides energy to half of the community has been deployed and tested for two years. This project was driven by the interest and governance of the Igiugig community, aided by the technical expertise of NREL (Kilcher et al., 2021a). The transparency and bottom-up governance allowed for the community's energy needs to be met sustainably for the future health of the entire Igiugig community.

There is a wide range of social data sets that could be considered during site selection. The most basic includes population data and the location of cities. This data is important for locating energy projects near communities that can use the resource, but it can also be used to identify communities in rural or remote areas that may benefit from access to reliable, clean energy sources. Social vulnerability data such as the Justice40 project or Center for Disease Control (CDC) data displays communities identified as vulnerable according to various criteria, which range from income, air quality, unemployment, energy cost, clean water access, and more. There is also climate change projection data, such as sea level rise models, showing which communities will be most impacted by climate change and need support in the clean energy transition. A final example is the National Oceanic and Atmospheric Administration’s (NOAA) fishery data, which displays critical commercial and recreational fishing locations. This data can be used to address use-conflicts in the marine space and for organizations to begin projects by creating mitigation strategies based on local activities.

## 2.4 Marine Spatial Planning

### *2.4.1 Introduction to Marine Spatial Planning*

As human activity combined with anthropogenic climate change contributes to the degradation of marine ecosystems, there is a need for thorough planning processes to be in place for future commercial ventures and other use cases in marine spaces to prevent further degradation. Marine spatial planning is an emerging method to provide this planning framework. Marine spatial planning (MSP) is defined as a process of "analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives, usually specified through a political process" (Ehler & Douvere, 2009). Spatial planning for terrestrial and coastal areas has been commonly used for years, but MSP has only recently been introduced and adopted globally. MSP is a comprehensive approach to marine resource management that seeks to address current and future marine uses sustainably.

MSP presents complex new difficulties (Backer, 2011). Firstly, marine spaces cover large areas and include both ocean waters and seafloor. Secondly, marine borders are more challenging to define than boundaries on land, and there are many governing bodies involved across the ocean. However, MSP allows for better coordination between the many management bodies in marine space. This includes bringing together fishing, maritime traffic, and environmental governing bodies to address use-conflicts. Furthermore, MSP provides the opportunity for transboundary cooperation, making addressing international issues easier (Backer, 2011).

Particularly with the rapid growth of the MRE industry to meet global climate goals, there is a further need for MSP (Azzellino et al., 2013; Backer, 2011). MRE projects are occurring in a landscape with many other overlapping users and activities. Therefore, MSP allows for efficient and effective planning for renewable energy projects while creating a more integrated marine management plan (Azzellino et al., 2013). This integrated approach enables conflicts to be identified and addressed early, along with increased stakeholder and public engagement.

### *2.4.2 Current Issues in the Marine Space*

There are many different industries and activities in the marine space. In the U.S., the list of maritime activities includes offshore renewable energy, shipping lanes, oil and gas, scientific research, coastal protection, cables and pipelines, mining, nature conservation, tourism and leisure, fishing and fisheries, underwater cultural sites, aquaculture, military, and ports (UNESCO, 2023). All these activities have their own governing bodies and strategic plans, but no synchronized effort exists. Furthermore, each industry faces unique legal and political challenges and dynamics (Smythe & McCann, 2018). MSP provides the perfect framework to integrate these different activities to create a coordinated inter-agency and inter-industry planning body. Additionally, current marine activities and planning exclude many stakeholders and public voices. MSP provides a framework for the inclusion of public input and more interactive engagement of stakeholders (Backer, H. 2011; Gopnik et al., 2012; Olsen et al. 2014).

### *2.4.3 Marine Spatial Planning Examples*

Rhode Island worked to create a marine spatial plan for both state and federal waters off the state's coast. The plan was established in 2011 and facilitated by the Rhode Island Coastal Resource Management Council (CRMC) and associates at the University of Rhode Island. The plan's ultimate goals were to achieve both marine conservation and sustainable economic development. The plan established various boards and committees, including a committee of technical and stakeholder experts. Furthermore, a guide was created for stakeholder engagement. Researchers have shown the many benefits of marine spatial planning for Rhode Island (Smythe & McCann, 2018). In particular, the committees were highlighted for establishing relationships among agencies and stakeholders early in the planning process. This promoted early engagement and collaboration, thus avoiding future conflicts. In addition, when conflicts appeared, these pre-existing relationships resulted in cooperation and mutual understanding among all parties to quickly address and work through issues. This would not be possible if these strong relationships between stakeholders were not previously established. Furthermore, researchers found that the MSP promoted clear communication and transparency among all agencies and stakeholders. Therefore, expectations were set early, and trust was established between groups (Smythe & McCann, 2018). This is especially important for facilitating businesses and agencies building strong relationships with local communities. Overall, Rhode Island's MSP has provided many benefits to the community and the marine ecosystem, and it acts as a model for the rest of the U.S.

MSP has also been used successfully to work with indigenous communities and First Nations to collaborate and coordinate on management plans for marine spaces. MSP calls for identifying all stakeholders and their values, thus allowing for the prioritization of indigenous land use and activities, while also allowing for structured use and sustainable development. One promising example occurred in British Columbia, Canada. This was a collaborative marine planning project between 17 First Nations governments and the British Columbia provincial government to create the Marine Plan Partnership (MaPP) (Diggon et al., 2021). The plan was created for marine uses spanning from northern Vancouver Island to the border of Alaska. The MaPP area was first divided into four sub-regions in order to have region-specific goals and strategies, which would also be integrated into a regional plan. The primary strategy for creating the MaPP was ‘community-based planning’, where First Nations created MSP for their respective territories based on their own values and needs, which were then used as the foundation to build sub-regional and regional plans. Researchers argue that this community-based strategy respects the rights, knowledge, and values of First Nation communities. From there, the provincial governance bodies acted as facilitators of regional collaboration while providing the necessary funding, additional technical tools, and expertise for planning. Researchers point to the plan’s community-based foundation, resulting in trust and transparency (Diggon et al., 2021). British Columbia’s MaPP provides a strong example of a successful MSP. The MaPP especially emphasizes the ability of MSP to include stakeholders and connect with local communities along with the equity that can be achieved.

In 2014, the European Parliament and Council established legislation under Directive 2014/89/EU to create a framework for marine spatial planning. The directive enforced the creation of legal frameworks by EU members for areas in the exclusive economic zone (EEZ), ocean area up to 200 miles off land territory in which nations have jurisdiction over resources (NOAA, 2023), to ensure sustainable development and ecological protection in marine spaces. The directive stated that all coastal nations must have implemented these MSPs by March 2021, and these plans must be reviewed every ten years. This directive aims to reduce conflicts, encourage investment in marine activities, increase economic cooperation between EU states, and prioritize the protection of marine ecosystems. The European Commission has supported its members through providing financial and technical support. The commission also emphasizes that the MSP is not a static plan; the vision is that this legislation will adapt and change as the European Green Deal increases sustainable marine development and the environmental landscape changes (European Commission, 2022).

In a 2022 report conducted by the European Commission, it was reported that over half (14/22) of member states had met the Directives deadline for implementing MSP, and several remaining member states were at an “advanced stage of producing draft plans” (European Commission, 2022). The report gave examples of successful member nations, and Ireland was used as an example of good public engagement and stakeholder involvement. The country had engaged in three months of public consultation to create the original baseline for its MSP, the country's first legislation of this kind. Furthermore, they held various public engagement events in coastal communities to increase public awareness about MSP and encourage local engagement in the planning process. The committee highlights this as an incredible example of creating a participatory and transparent process. The review report also highlighted common challenges throughout states, such as the complexity of multi-sector and multi-objective planning. This complexity has been identified as the most significant challenge in MSP. Furthermore, the report identified data collection and compilation as a challenge, especially across nations. The legislation (Directive 2014/89) and success across EU states provide an excellent framework that other nations can follow, especially the U.S., where specific states are allowed to create local MSPs independently.

### 2.5 GIS and Multi-Criteria Decision Analysis

Geographic information systems (GIS) can be used to quickly visualize geospatial data, especially data representing the different criteria that determine optimal sites for renewable energy projects (Mueller & Wallace, 2008). A compilation of this data is important for guiding renewable energy site selection. However, the differing types of qualitative and quantitative data make concurrent analysis difficult, especially on large geographic scales. GIS-integrated analytical tools can be used to analyze typically incompatible data types, which provides a powerful tool to conduct site selection that integrates different kinds of criteria (Ali et al., 2020; Peters et al., 2020). Multi-criteria decision analysis (MCDA) is one geospatial analysis method that allows for evaluating multiple, usually overlapping, criteria to identify the most suitable site locations.

GIS MCDA methods for site selection have been developed and used extensively in the renewable energy field. For example, substantial literature exists regarding siting onshore wind energy projects (Kocabaldir & Yücel, 2020; Bennui et al., 2007; Tegou et al., 2010; Effat & El-Zeiny, 2022; Watson & Hudson, 2015), which has helped provide a framework for research in offshore wind energy extraction. Peters et al. (2020) reviewed the uses of GIS for offshore wind energy research and created a framework for future usage. The most common research objective of the papers analyzed was resource assessment, whereas the second most common was site selection. Peters et al. identified the most common criteria as maximum water depth and altitude of wind assessment. Across all papers, the most variability existed in the spatial resolution of the data used. Peters et al. did not find that this was a result of differing locations or time of study; thus, the authors emphasized the consideration of spatial resolution of data for future study. Finally, the study highlighted that most researchers justified using GIS by emphasizing its compatibility with managing multiple spatial datasets (Peters et al., 2020). Similarly, literature on solar PV energy site selection using GIS is also well established. Deveci et al. (2021) conducted an extensive review of studies that combined GIS and decision-making analysis for

PV energy site selection. The study identified key sub-criteria and organized them into three main categories: technical, economic, environmental, and social or political. The majority of studies reviewed used the Analytical Hierarchical Process (AHP) combined with GIS for site selection methods (Deveci et al., 2021).

A review of MCDA applications for renewable energy site selection (Shao et al., 2020) identified similarities in the criteria used for onshore wind and solar energy projects. The review identified criteria that were classified as exclusionary, meaning areas with these factors are automatically considered unsuitable. The most frequent exclusionary criteria for both onshore wind and solar projects were bodies of water, protected areas, urban areas, and roads. Technical criteria were highly valued, such as solar irradiance, wind speed, and temperature, which all impact the energy extraction potential. Other important criteria were proximity to roads, transmission lines, and residential areas. The solar and wind industries are more mature; thus, the selection criteria have been thoroughly reviewed and established. In the marine energy literature, there were fewer similarities in criteria across projects. However, the most common exclusionary criteria were a minimum energy resource, a minimum or maximum distance from shore, marine protected areas, military exercise areas, and minimum or maximum water depth (Shao et al., 2020). Over half of the papers used AHP for the criteria weighting method due to its ability to eliminate bias and compare complex criteria relatively simply (Shao et al., 2020). Over half of researchers used GIS to complete the weighted analysis to visualize site suitability. Overall, Shao et al. (2020) show the similarities and differences in criteria across renewable energy site selection. These established guidelines for criteria used in solar and wind projects can help guide the selection of criteria for marine energy projects.

A common benefit highlighted in studies was the application of GIS MCDA to address use conflicts and combine criteria for optimized site planning. A study in Australia used GIS MCE to evaluate sites to limit conflict with other marine space users (Flocard et al., 2016). However, the study did not include any social or environmental justice data. Hosseinzadeh et al. (2023) conducted a comprehensive review of combined offshore wind and wave energy site selection by looking at 27 papers from 2009-2022. The most common exclusionary criteria were areas too close or too far from shore, MPA, military exercise areas, and shipping lanes (Hosseinzadeh et al., 2023). The specific criteria selected for evaluation varied across papers. Researchers identified the most frequently used criteria across all literature reviewed (criteria used by more than five articles), which were criteria representative of the energy resource potential, bathymetry, distance to ports, distance to shore, and shipping density. Only two papers were identified as considering socioeconomic data. Hosseinzadeh et al. (2023) categorized the specific site analysis methods used. Roughly half of the studies reviewed utilized MCDA methods; the other most common method used was a resource-based analysis (Hosseinzadeh et al., 2023), which only evaluates techno-economic criteria and does not account for any social or environmental factors. Of the MCDA papers reviewed, half used GIS to conduct analysis, and the specific weighting methods varied. Hosseinzadeh et al. (2023) identified subjective weighting as the most common criteria weighting method. This study helped demonstrate general trends in site selection research for combined wind and wave energy projects.

Shao et al. (2020) analyzed 85 papers from 2008-2018 in a comprehensive review of MCDA applications for renewable energy site selection. Of the papers analyzed, 96% were on solar and wind (onshore) energy research. Furthermore, only 7% of research was conducted in study areas in the U.S. (Shao et al., 2020). The review analyzed criteria used by separating papers by energy resource and then identifying similarities across all projects. However, very few documented studies use GIS-based MCDA in the marine energy field. Shao et al. (2020) identified only 14 marine energy papers (7 offshore wind, 3 wave, 2 tidal, 2 offshore wind and wave). Furthermore, most of the literature in the marine energy field pertains to offshore wind (Vagiona & Kamilakis, 2018) and hybrid wind and wave systems (Hosseinzadeh et al., 2023; Vasileiou et al., 2017). The literature that utilizes GIS-based methods for marine energy site selection primarily focuses on the energy resource and techno-economic considerations, thus leaving out social or environmental justice data. Furthermore, when GIS MCDA is used, the criteria weighting method is rarely done statistically. There is also a general lack of research with study areas focused on the U.S., demonstrated in Figure 2.1, which displays the literature that applied MCDA methods for marine energy site selection (offshore wind, combined wind and wave, wave, tidal).

*Figure 2.1 Geographic locations of existing studies using GIS and MCDA methods for marine energy site selection. Of the papers displayed, the energy resources studied were four offshore wind (Tauofik and Fekri, 2021; Tercan et al., 2020; Mahdy and Bahaj, 2018: Elgabiri et al., 2020), three wave (Flocard et al., 2016; Kamranzad and Hadadpour, 2020; Nobre et al., 2009), three tidal (Defne et al., 2011; Lee et al., 2017; Wu et al., 2017), and four combined wind and wave (Azzellino et al., 2013; Azzellino et al., 2019; Cradden et al., 2016; Vasileiou et al., 2017).*

### *2.5.1 Criteria Weighting*

A fundamental part of the MCDA process is the weighting of criteria, which evaluates the relative importance of each criterion to assign specific criteria weightings. There are many different methods used by researchers. Equal weighting is the simplest method, where all criteria are assumed to be of equal importance and given an equal weight. Researchers Baban and Parry (2001) applied this method for an analysis of wind farms in the UK. The total weighting must be equal to 100%, so since 14 criteria were used, each criteria weight was calculated to be 7.14% (Baban & Parry 2001). The analysis created a successful map of the UK displaying site suitability on a scale of 0 (not suitable) to 10 (highly suitable) (Baban & Parry 2001). This is a straightforward method; however, the resulting map does not reflect the complexity of site selection decisions where all criteria are not equally important. For example, for this wind farm site selection, assigning equal weights to all factors might overlook the significance of environmental impact in favor of other factors. As a result, sites with a high wind resource but significant environmental impacts could be favored over less impactful alternatives. Using a different method for weighting allows for the prioritization of minimized environmental impact, resulting in a map that prioritizes areas with a balanced environmental impact and wind resource.

Subjective weighting is also a simple method, thus commonly used, where a single expert assigns the weightings to criteria based on their knowledge and personal judgment (Hosseinzadeh et al., 2023). For example, Janke (2010) conducted a MCDA analysis using GIS to identify areas in Colorado that are most suitable for wind and solar farms. For this analysis, Janke used his expertise and personal preference to rank the specific criteria. Examples of criteria used are wind potential, solar potential, distance to cities, distance to transmission lines, distance to roads, and land cover. The results successfully identified suitable locations in Colorado for both wind and solar farms. However, a key limitation of the study was that there was little rationale or cited research to support the criteria weightings. This is one of the disadvantages of the subjective weighting method, as well as the lack of a standardized or systematic approach.

The most frequent renewable energy site selection method is the AHP method which is a hierarchical approach to complex decision making (Ilbahar et al., 2019; Shao et al., 2020). The AHP involves pairwise matrices to calculate overall weightings. This means individually comparing criteria against each other and using a scale to reflect relative importance. A matrix is then used to calculate overall weightings, which reflect each individual criteria’s importance relative to all other criteria. AHP is popular because it provides a structured approach to quantifying complex and subjective judgements (Vasileiou et al., 2017). For example, Vasileiou et al. (2017) selected AHP as their criteria weighting method for analysis of hybrid wind and wave sites in Greece. The authors used GIS software to conduct an AHP analysis for eight criteria representing economic, technical, and socio-political factors. Twelve sites in Greece were identified as suitable for the deployment of hybrid wind and wave sites in Greece. The authors concluded that the use of AHP for criteria weighting significantly reduced the subjectivity in judgments. Many other examples of literature have applied AHP for criteria weighting (Elgabiri et al., 2021; Lemos Bulhões et al., 2020; Moradi et al., 2020; Watson & Hudson, 2015). One limitation of AHP analysis is the assumption that all criteria are independent (Ilbahar et al., 2019). For example, if the two criteria being analyzed are proximity to ports and proximity to the electric grid, the assumption is that these two criteria are independent of each other. However, oftentimes this is not the case, because optimal port and transmission locations may coincide. Ports are often located in areas with well-developed infrastructure, including energy infrastructure, to support port operations and nearby industries. Therefore, sites close to ports might also be close to transmission lines, meaning some interdependence exists between the two criteria.

The Analytical Network Process (ANP) expands on the AHP method by considering the dependencies and interactions between criteria (Shao et al., 2020). Instead of creating a straightforward hierarchy, ANP creates a network between the criteria. This can create a more comprehensive analysis by including the interactions between criteria, however, the analysis involves complex calculations which can be time-consuming. Researchers Atmaca and Basar (2012) used ANP to evaluate the suitability of six different types of power plants in Turkey. The major criteria evaluated were technology, economy, quality of life, and socio-economic impacts

(Atmaca & Basar, 2012). There are other less common methods for criteria weighting that are further discussed in the comprehensive review conducted by Shao et al. (2020).

## 2.6 Study Goals

As explained above, GIS-based MCDA is an established method for site selection in renewable energy, however, its use within the complex area of marine energy applications lacks substantial research. This paper attempts to fill these gaps in the literature and successfully apply GIS-based MCDA methods for marine energy site selection. By conducting site selection studies in two distinct locations in the U.S. with different technical and socioeconomic conditions, this research seeks to contribute to this underexplored area of literature. Study results provide empirical evidence and insights into the strengths of GIS-based MCDA for different marine energy applications. This investigation also prioritizes integrating social and environmental justice data, recognizing their role in enhancing the strength of site selection research.

# 3 Methods

The project utilized GIS-based MCDA methods to evaluate marine energy project sites in Puerto Rico and Hawaiʻi. For each study, specific criteria were selected based on the location's unique communities and energy systems. AHP methods were applied to calculate criteria weightings because the method provides a structured approach to making complex siting decisions. GIS was used to create three final suitability maps for each area: a resource overlay, a technical overlay, and a social justice overlay. Finally, a comparative analysis was made on the technical and social justice suitability maps within each study area.

## 3.1 Study Area Selection

Before conducting the site selection analysis, a study area extent was selected. This allows for more accurate and higher-resolution geospatial data to be used for analysis. Each area has its own unique communities, energy resource potential, and other variables that must be considered. Traditionally, locations with the highest energy resource (wind speeds or wave energy) are considered the most suitable. Whereas the energy resource is important, many other variables should also be considered as there are many valuable motivations for selecting sites with lower energy resources.

### *3.1.1 Puerto Rico Study*

The first study area is the territory of Puerto Rico, which includes the main island, and to the east, Isla Culebra and Isla Vieques (Figure 3.1). Puerto Rico has been subjected to increasingly severe tropical storms, which have caused significant damage to the territory (Barreto-Orta, 2013; PRCC, 2013). Many of the communities not a part of the main metro area experienced loss of power and damaged infrastructure during these storms, and they have spent years rebuilding from these damages (Barreto-Orta, 2013; PRCC, 2013). For example, more than a month after Hurricane Maria hit the Island in 2017, 75% of the island residents remained without electricity (Houser & Marsters, 2017). Furthermore, researchers found that low-income and energy-insecure households faced longer wait times to have their energy restored in comparison to other households (Sotolongo et al., 2021). During disasters, minority communities already experience heightened impacts, so restricted energy access only exacerbates these impacts. Site selection decisions must include data identifying these high-risk communities in order to address these injustices. Social justice data can also help highlight communities that are at most risk due to climate change and prioritize sites that most need coastal protection. Furthermore, the energy produced by CSI-WECs would support the energy resiliency of Puerto Rican communities. This green energy would also contribute toward Puerto Rico's goal of meeting its electricity needs with 100% renewable energy by 2050 (DOE, 2022).

Esri, NASA, NGA, USGS, Esri, TomTom, Garmin, Foursquare, SafeGraph, FAO, METI/NASA, USGS, NPS, USFWS

*Figure 3.1 Map of Puerto Rico study area*

### *3.1.2 Hawai‘i Study*

The second study area is the islands of Hawai‘i, which is pictured in Figure 3.2 and encompasses the Big Island, Maui, O’ahu, Lanai, Molokai, Kuai, and Ni’ihau. The Hawaiian Islands are in the Pacific Ocean, which provides a large untapped energy resource. The inland areas of Hawai‘i are characterized by tall volcanic mountains, but the lower coastal areas of the islands are at high risk to sea level rise. The coastal areas are densely populated and host most of the economic activity. The future sea level rise projections for the region of Hawai‘i are estimated to be 20%-30% higher than the global mean (City and County of Honolulu, 2018). Honolulu, the capital and largest city of Hawai‘i, is one of the most vulnerable urban areas in the U.S. to future sea level rise. The area is predicted to experience 1.3 ft (0.4 m) to 5.8 ft (1.78 m) of sea level rise by 2100 (City and County of Honolulu, 2018). Due to the high density of economic activity vulnerable to sea level rise, a 3.2 ft (0.98 m) rise would result in an economic loss of 66% for the state (Hawai‘i Climate Change Mitigation and Adaptation Commission, 2017). Overall, Hawai‘i will be severely impacted by climate change, thus the state has a vested interest in reducing its carbon emissions and investing in renewable energy. Furthermore, Hawai‘i is one of the most petroleum-dependent states in the U.S., and the state consumes seven times more energy than it produces (EIA, 2023b). Consequently, the state has some of the highest energy costs in the country (EIA, 2023b). This provides further motivation for the state to develop a larger renewable energy portfolio to strengthen its energy independence and resiliency. In 2015, Hawai‘i became the first state to create legislation mandating a goal of 100% renewable energy by 2045 (Hawai‘i State Clean Energy Initiative [HCEI], n.d.). Hawai‘i has a wide range of renewable energy sources to choose from, including geothermal, wind, solar, and wave energy. This makes a hybrid wind-wave-solar project a perfect fit for the Hawaiian Islands. Collocation of these energy resources can help address the intermittency concerns of most renewable energy sources. However, in the past, Native Hawaiians have experienced deep social injustices, including directly due to the actions of Hawaiian utility companies (Kokal, 2020). For example, Kokal (2020) describes the population of Kapolei, O’ahu, a majority native Hawaiian community, facing the highest rates of asthma and cancer. They are located next to the Kahe power plant, a major source of pollution. Kahuku is a town on the northern shore of Oahu and is also a majority native Hawaiian community. Another example is the Kahuku Wind Turbine Project, which was constructed near schools and neighborhoods, against strong local objections.

Community members state that there was no local engagement or attempt to listen to their concerns (Kokal, 2020). There is a need to acknowledge and honor the cultural heritage of native Hawaiians. This is why social and environmental justice factors are especially important for this hybrid systems study.

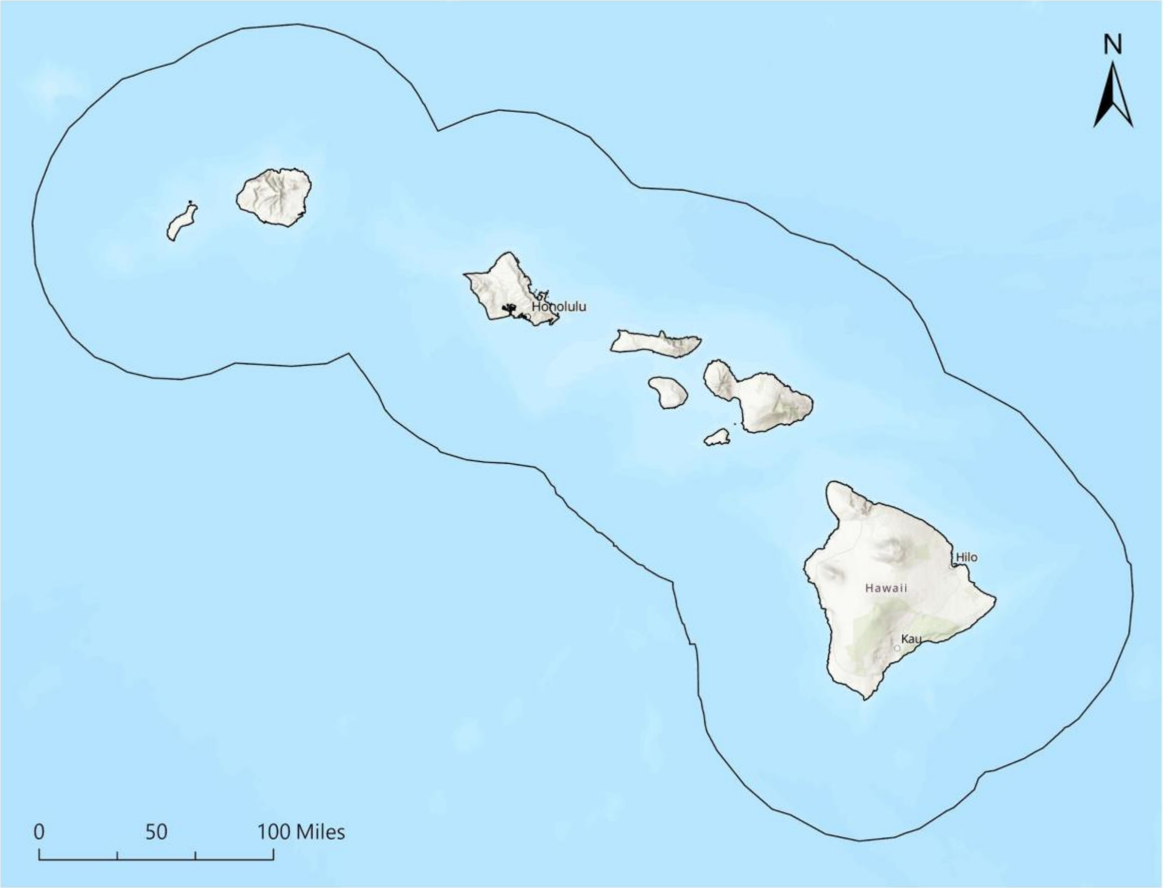


*Figure 3.2 Map of Hawai'i study area*

## 3.2 Criteria Selection

The criteria selected reflect the study area's unique community, resource potential, and stakeholders. Geospatial data for both studies were cataloged. Many of the final criteria selected were also used in other marine energy MCDA research. However, some social and environmental justice data are novel additions. It is important to note too that criteria can be limited by data availability, quality, or compatibility. For example, remote or island areas such as Puerto Rico and Hawaiʻi sometimes lack the same quantity and quality of geospatial data in comparison to U.S. mainland areas. Quality refers to the spatial resolution of the data.

### *3.2.1 Puerto Rico Study*

In Puerto Rico, the criteria selected for analysis were distance from shore, the wave energy resource, proximity to cities, proximity to transmission lines, proximity to ports, proximity to Justice40 climate change and energy disadvantaged communities, and military danger and restricted zones. Some criteria identified as important from the literature review were not included due to data availability, such as hurricane risk data. In Puerto Rico, military danger and restricted zones were used as exclusionary criteria. MPA areas were considered, but not included due to the nature of CSI-WEC technology being essentially onshore.

#### *3.2.1.1 Distance from Shoreline*

A standardized CSI-WEC device design does not exist; thus, there are no strict guidelines for water depth or distance from shore. However, existing and proposed project sites are onshore or near-shore, so the data layers were clipped to an offshore extent of three nautical miles (nm). This encompasses the distance within which all existing wave energy projects have been located. Furthermore, 3.0 nm is a common state jurisdiction boundary used nationally by coastal states as defined by the Coastal Zone Management Act.

#### *3.2.1.2 Wave Energy Resource*

The wave energy resource is important for understanding the economic and technical feasibility of the project. Whereas the energy resource should not be the only criteria considered, it is important that CSI-WECs will be producing some amount of energy, and energy production estimates help plan for energy application planning. The wave energy resource was represented by data from 42-year average (theoretical) omnidirectional wave power provided by Sandia National Laboratory (Allahdadi et al., 2021; Ahn et al., 2022). Omnidirectional wave power (kW/m) is the total energy flux arriving from all directions at a point; it is often used as a summary metric to show the theoretical energy resource.

#### *3.2.1.3 Proximity to Cities*

Proximity to cities is used for finding the population that will be served by the CSI-WEC installation. It is ideal to locate the projects close to the largest populations, in order to ensure maximum energy benefits. City data was pulled from the Marine Cadastre tool managed by the Bureau of Ocean Energy Management (BOEM) and NOAA's Office for Coastal Management (Office for Coastal Management [OCM], 2023a).

#### *3.2.1.4 Proximity to Transmission Lines*

Proximity to transmission lines is important for estimating costs associated with grid connection and energy transport. Transmission lines can also be an indicator of other energy infrastructure which is important for installation and operation of CSI-WECs. However, for CSI-WECs proximity to powerlines is less important because of the ability for energy produced to directly operate smaller-scale applications, such as desalination projects. Powerline location data was collected from the Homeland Infrastructure Foundation Level (HIFLD) Database (HIFLD, 2024).

#### *3.2.1.5 Proximity to Ports*

Proximity to ports is important because port infrastructure can make installation and maintenance of CSI-WEC projects easier and more efficient. For Puerto Rico, ports are also being used as a surrogate for the proximity to existing coastal protection structures, as most breakwaters and jetties are built near ports and harbors. Identifying locations with existing coastal structures is crucial for recognizing areas that have historically needed protection. Additionally, it helps identify structures that could be replaced by or upgraded to a CSI-WEC. Port location data was pulled from the Marine Cadastre tool managed by BOEM and NOAA Office for Coastal Management (OCM, 2023b).

#### *3.2.1.6 Justice40*

Justice40 is a federally funded initiative that has mandated environmental justice action. The initiative ensures that 40% of environmentally related federal investments are appropriated to environmentally burdened communities. Disadvantaged communities are defined as communities that are marginalized, underserved, and overburdened by pollution. This is measured with data sets that represent indicators such as energy cost, health outcomes, housing costs, wastewater discharge, and linguistic isolation. Through the Justice40 initiative, national geospatial data is available that identifies census tracts as disadvantaged or advantaged, along with specific categories of indicator data. The eight categories are climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development. This data is important to include for addressing environmental justice concerns. It allows for the identification of communities that have historically been marginalized and underfunded, and thus could potentially benefit from the addition of a renewable energy project.

For Puerto Rico, two specific categories were selected from the national Justice40 dataset, and proximity to these communities was calculated and used for the analysis. The first specific dataset identified communities disadvantaged due to climate change risks (Climate and Economics, 2023). Communities identified as disadvantaged are census tracts that are at or above the 65th percentile for low-income and at or above the 90th percentile for expected agricultural loss, expected building loss rate, expected population loss rate, projected flood risk, or projected wildfire risk. The second identified communities disadvantaged due to energy access and efficiency (Climate and Economics, 2023*)*. Communities identified as disadvantaged are census tracts that are at or above the 90th percentile for projected energy costs and are at or above the 65th percentile for low-income.

Energy justice researchers (Caballero et al. (2023) emphasize that identifying communities that have received less investment in infrastructure and endure frequent power outages helps to prioritize creating equitable energy infrastructure development and MRE projects. In Puerto Rico, many of the local communities do not have reliable access to energy, after Hurricane Maria it took over a year for power to be fully restored to all residents (Houser and Marsters, 2017). By including and prioritizing community energy access as a criteria, the final proposed sites should aid communities that need access to clean energy the most. A CSI-WEC may help one community get reliable energy months earlier.

### *3.2.1.7 Exclusionary Criteria*

The only exclusionary criteria used were military danger and restricted areas, where access and development are generally heavily restricted or prohibited. These are displayed in Figure 3.3. Military danger and restricted zones were collected from the Marine Cadastre tool managed by BOEM and NOAA Office for Coastal Management (OCM, 2024). After the analysis was completed, the exclusionary zones were overlaid on the final suitability maps.

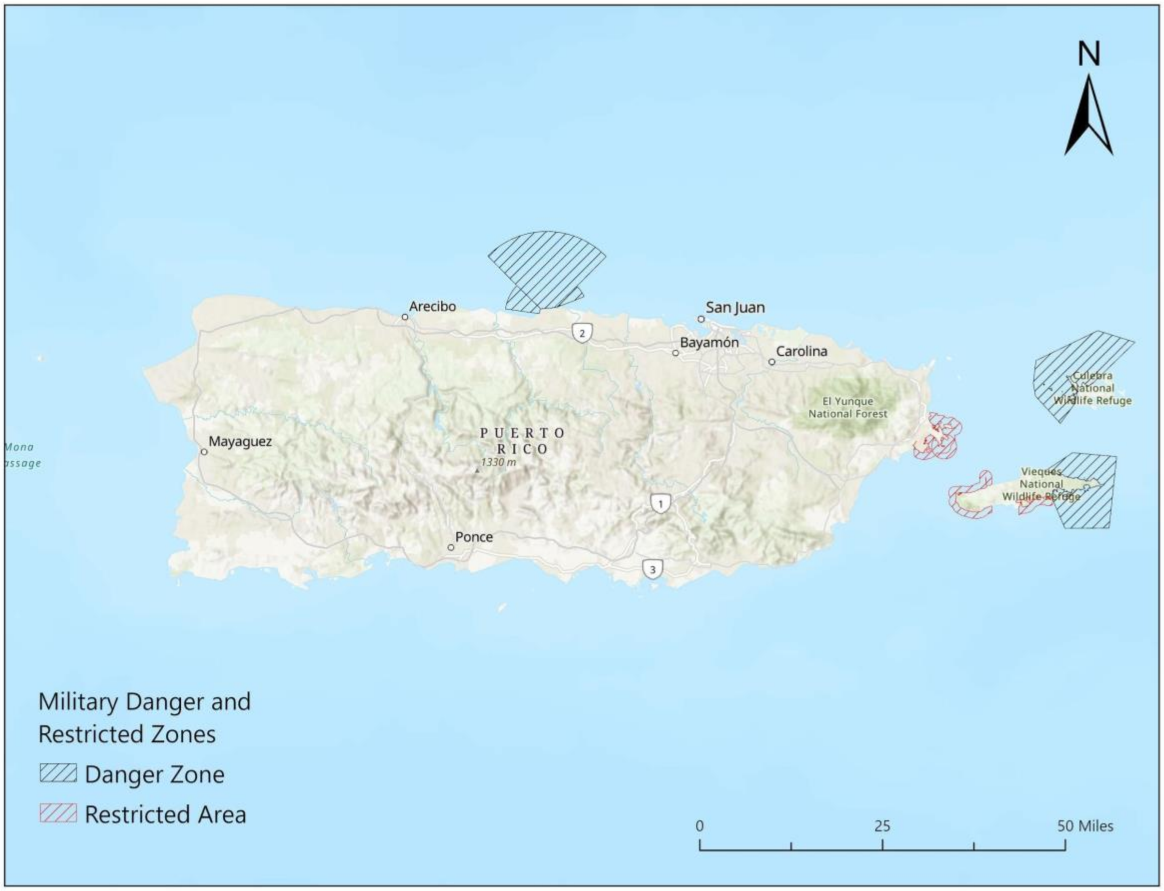


*Figure 3.3 Puerto Rico military danger and restricted zones*

### 3.2.2 Hawai‘i Study

In Hawai‘i, the criteria selected for analysis were the wave power, wind speed, solar irradiance, proximity to transmission lines, proximity to ports, distance from Justice40 disadvantaged communities, military danger and restricted zones, and Marine Protected Areas (MPA). Solar and wind energy resource data were not included in the Puerto Rico study because this data is only applicable to the hybrid system used in the Hawai‘i study.

#### 3.2.2.1 Wave Energy Resource

The wave energy resource is important for understanding the economic and technical feasibility of the project. Again, the wave resource was characterized by omnidirectional wave power data (kW/m). The dataset was obtained from NREL’s Marine Energy Atlas and was generated using WaveWatch III and SWAN models. The dataset is an annual 32-year average from 1979 to 2010. (Li et al., 2021).

#### 3.2.2.2 Wind Energy Resource

The wind energy resource is important for understanding the economic and technical feasibility of the project. The wind energy resource was characterized by average annual wind speeds at 100 meters above the surface level generated from WIND Toolkit data provided in a geo-database obtained from NREL (Draxl, 2015). The dataset spans seven years from 2007-2013.

#### *3.2.2.3 Solar Energy Resource*

The solar energy resource is important for understanding the economic and technical feasibility of the project, and especially important for projections of energy production. The solar energy resource was represented by the global horizontal solar irradiance (GHI) from NREL's RE Atlas, which was created using the SUNY Satellite Solar Radiation Model (Lopez et al., 2012; Perez, 2012). The model utilized local satellite data to incorporate cloud coverage, which reduces solar radiation that reaches the earth's surface. The data was averaged from an eight-year hourly model (1998-2009). The annual average daily solar resource is represented by kWh/m²/Day.

#### *3.2.2.4 Proximity to Transmission Lines*

Proximity to transmission lines is important for estimating costs associated with grid connection and energy transport. Transmission lines can also be an indicator of other energy infrastructure which is important for installation and operation of hybrid systems where storage is critical for dealing with energy variability. Transmission line location data was collected from the Homeland Infrastructure Foundation Level Database (HIFLD, 2024).

#### *3.2.2.5 Proximity to Ports*

Proximity to ports is important as port infrastructure makes the installation and maintenance of hybrid projects easier and more efficient. It can also impact the economic feasibility of a project. Port data was pulled from the Marine Cadastre tool managed by BOEM and NOAA Office for Coastal Management (OCM, 2023b).

#### *3.2.2.6 Justice40*

The Justice40 dataset is explained thoroughly in section 3.2.1.7. For Hawaiʻi, the general dataset was used, which classifies communities as disadvantaged if they are in a census tract that meets the thresholds for at least one of the categories of burden or if they are on land within the boundaries of a Federally Recognized Tribe (Climate and Economics, 2023). This is an important indicator of communities that have been historically underserved or burdened, and many census tracts are areas where there are large populations of Native Hawaiians. Climate change will have a disproportionate impact on the traditional lifestyle and cultural practices of indigenous communities in Hawaiʻi (Leong et al., 2014). However, in recent pushes for renewable energy projects in Hawaiʻi, there have been numerous projects proposed in locations that impact land or activities that are critical to the cultural and social well-being of Native Hawaiians. These projects will only further the harm to indigenous Hawaiian communities, and with the historical social injustices, it is vital that future renewable energy projects actively mitigate any adverse impacts on the lives of indigenous communities. Therefore, locations closer to these Justice40 tracts will be considered less suitable, in order to create a buffer around these communities.

#### *3.2.2.7 Exclusionary Criteria*

Military danger and restricted zones were also used exclusionary criteria in Hawaiʻi, along with MPA. These are displayed in Figure 3.4. The MPA map encompasses National Marine Sanctuaries and Marine National Monuments, where development and disruptive activities are heavily managed in order to protect sensitive marine environments, species, and cultural heritage sites. This is especially important in Hawaiʻi which is home to the Humpback Whale National Marine Sanctuary. MPA locations were obtained from NOAA’s Marine MPA website (OCM, 2024b). Military danger and restricted zones were collected from the Marine Cadastre tool managed by BOEM and NOAA Office for Coastal Management (OCM, 2024). Once the analysis was completed, the exclusionary zones were overlaid on the final suitability maps.

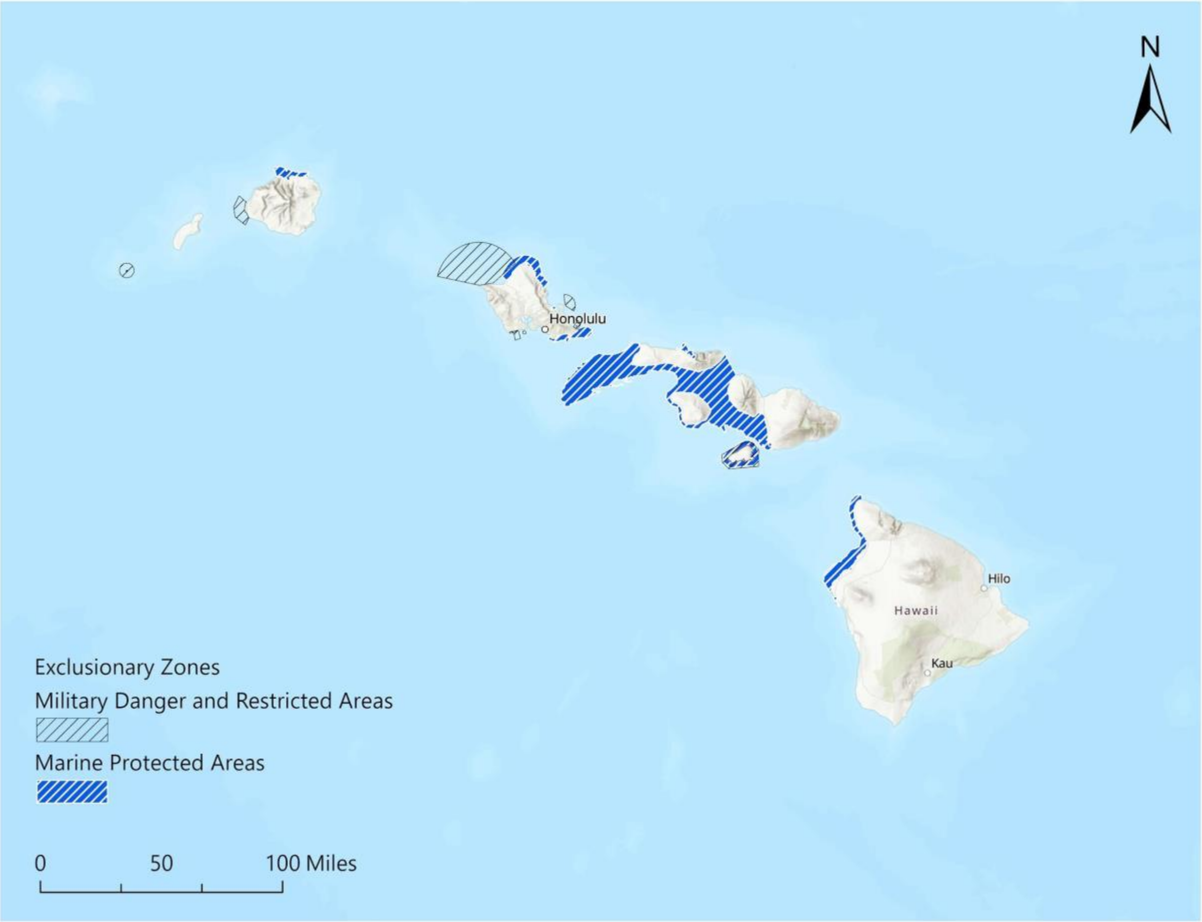


*Figure 3.4 Map of Hawaiʻi study area and exclusionary zones: MPA locations and military danger and restricted zones*

## 3.3 Criteria Weighting

AHP pairwise comparison matrix analysis was conducted in the computer programming language Python. The AHP process was created by Thomas Saaty (1990) and involves assigning values to pairwise comparisons that represent the relative importance of one criterion over another. These values are listed in Figure 3.1 and are used to create a pairwise comparison matrix. Within the matrix, the values in each column were summed. Then the matrix was normalized by dividing each point in the matrix by the column's sum to create values from 0 to 1. Finally, the average of each row was calculated. The output was a criteria weighting, which represents the criteria's overall importance in comparison to all other criteria. To validate the criteria weightings and test for robustness, a Consistency Index (CI) and Consistency Ratio (CR) were calculated in Python using Equation 1 and Equation 2 (Vasileiou et al., 2017).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad [1]$$

$$CR = \frac{CI}{RI} \quad [2]$$

Where $\lambda_{max}$ is the maximum eigenvalue of the matrix and $n$ is the number of criteria in the matrix. RI is the Random Index, a standard value derived from the size of the matrix. This value was calculated by Saaty (1990) who created a table of RI values based on matrix size. This value increases with matrix size. If the CR is greater than 10% then the pairwise comparisons are not consistent and should be repeated (Vasileiou et al., 2017).

| **Intensity of Importance** | **Definition** | **Explanation** |
|---|---|---|
| **1** | Equal Importance | Two criteria contribute equally to the objective |
| **3** | Moderate importance | Experience and judgment slightly favor one criteria over another |
| **5** | Essential or strong importance | Experience and judgment strongly favor one criteria over another |
| **7** | Very strong importance | A criteria is favored very strongly, and its dominance is demonstrated in practice |
| **9** | Extreme importance | The criteria favoring one activity over another is of the highest order of affirmation |
| **2, 4, 6, 8** | Intermediate values | |

*Figure 3.1 AHP value scale chart based on Saaty (1990).*

### 3.4 GIS/MCDA methods

After the selection of the study areas and specific criteria, data was imported and clipped to the extent of the study location using the ESRI GIS software ArcMap 10.8.2 (ESRI 2011). The study area extent was 3.0 nm in Puerto Rico and 50 nm in Hawai‘i. The following steps are also described in a flow chart pictured in Figure 3.2. Data was reprojected to the same geographic coordinate system to ensure compatibility across data layers. For Puerto Rico, the Projected Coordinate System (PCS) Puerto Rico SPCS NAD 1983 was used. For Hawai‘i, Hawai‘i’s State Plane Coordinate System (SPCS) NAD 1983 UTM 4 was used. The Euclidean distance was used to calculate the proximity for feature class data (city locations, port locations, Justice40 disadvantaged communities, and electric transmission lines), providing the distance between the layer feature and each raster cell. To allow for the compilation of the data layers, each layer was normalized to a standard scale of 0 to 1, where 1 is considered the highest rank, and 0 is the least desirable. This was done with the Raster Calculator using Equation 3:

$$Raster = 1 - \frac{Raster\ - Raster\ Minimum}{Raster\ Maximum - Raster\ Minimum} \qquad [3]$$

By subtracting from 1, the equation ensures that higher values are associated with the closest proximity (and highest suitability).

In ArcGIS, the data layers were combined using the Weighted Sum tool. The criteria rankings from the AHP analysis were used to weight each data layer. After the analysis was completed, exclusionary areas were overlaid to remove locations classified as unsuitable. The resulting raster displayed the variability of suitability of sites in the study area.

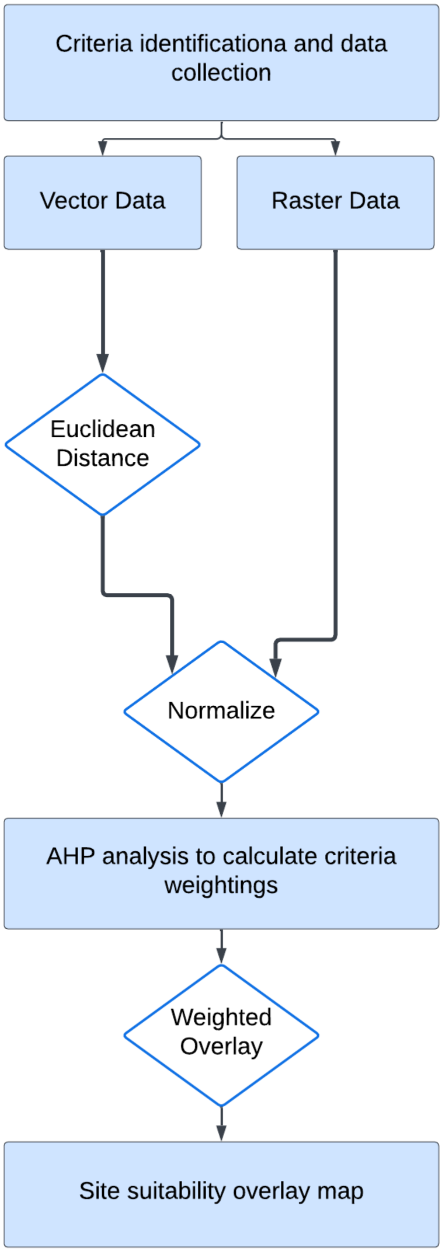


*Figure 3.2 Flow chart of GIS and AHP methods used to create site suitability maps. Diamond shapes indicate a GIS tool.*

## 3.5 Comparative Analysis

Once the initial weighted overlay was created, another analysis was completed without the social justice layers included but keeping the weightings of the other criteria the same. For Puerto Rico, this meant removing the two Justice40 proximity layers, and for Hawaiʻi the one Justice40 proximity layer. For further comparison, another map was created by using the Raster Calculator tool to subtract the social justice overlay from the technical. This created a difference map that illustrates the differences between final site rankings between each analysis. With the creation of these results, there were four site suitability maps to compare between each study. The first is an energy resource map, the second is a site suitability analysis with only the resource and technical criteria, the third is a complete site suitability analysis including social criteria, and the final map illustrates the differences between analyses.

## 3.6 Measures of Success

The first measure of success is the creation of a site suitability map in ArcGIS. The next measure of success is that the suitability map clearly identifies areas that range from not suitable to highly suitable and at least one site is identified as highly suitable. Highly suitable sites are defined as sites ranked in the highest quartile of the results, ideally from 0.75 to 1. Whereas, highly unsuitable sites are defined as sites ranked in the lowest quartile of results, ideally between 0 and 0.25.

# 4 Results

In total, eight maps were created across the two study areas. These include an energy resource map, two suitability maps, one technical map with social criteria omitted and one with social criteria included, and a difference analysis map for each case study. There are clear differences between the output maps within study areas. Furthermore, there are differentiations between the impact of the social justice data on the overlay results between study areas.

## 4.1 Puerto Rico Case Study

The criteria weights used during the suitability analysis were created from an AHP analysis (Figure 4.1). The highest weighted criteria were the Justice40 energy disadvantaged communities and climate change disadvantaged communities. The consistency ratio was 4.1%, showing that the criteria weight matrix was consistent. The omnidirectional wave power map (Figure 4.2) shows that there is a strong wave resource along the north shore of Puerto Rico, with values at roughly 13 kW/m. Figure 4.3 displays the two site suitability maps: the overlay with social justice criteria and the technical overlay without social justice criteria. The first analysis used these criteria: Justice40 climate change disadvantaged communities, Justice40 energy disadvantaged communities, wave power, port proximity, city proximity, and transmission line proximity. This map overlay shows that there are many suitable CSI-WEC sites around the island. The northern shore near San Juan is highly suitable, as well as small patches on the southern shore. The second analysis used these: wave power, port proximity, city proximity, and transmission line proximity. This map overlay shows that the most suitable CSI-WEC sites are along the north shore of Puerto Rico. The most favorable sites are clustered around the city of San Juan, the NE corner of the island, and the NW corner of the island. The sites with suitability values over 0.751 are considered highly suitable, while those with values less than 0.45 are considered unsuitable. This applies to both maps. The final map displays the difference between the technical and social justice map overlays (Figure 4.4) showing that the inclusion of social justice data creates different results. In particular, the sites on the southern coast of Puerto Rico were scored significantly higher when the social justice criteria were included in the first analysis.

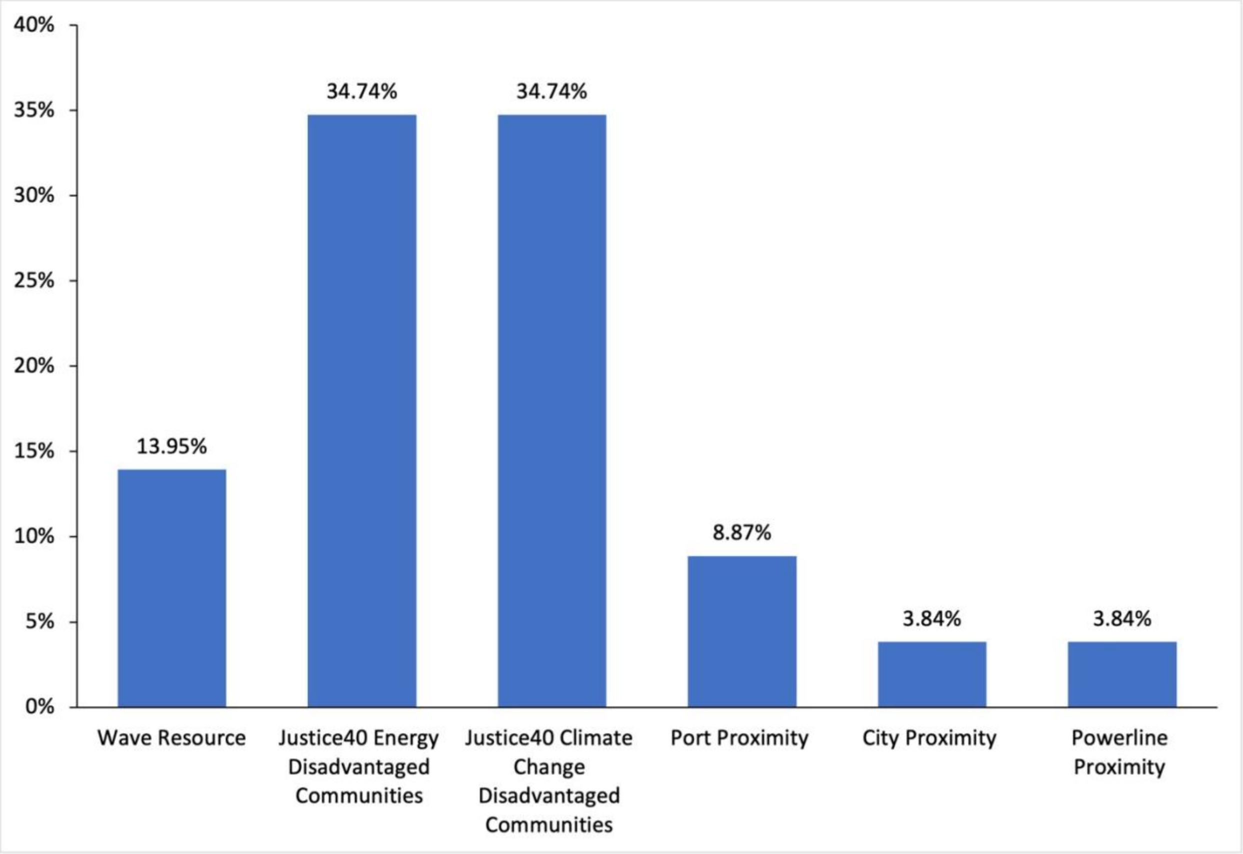


*Figure 4.1 Puerto Rico criteria weightings calculated from the AHP analysis*

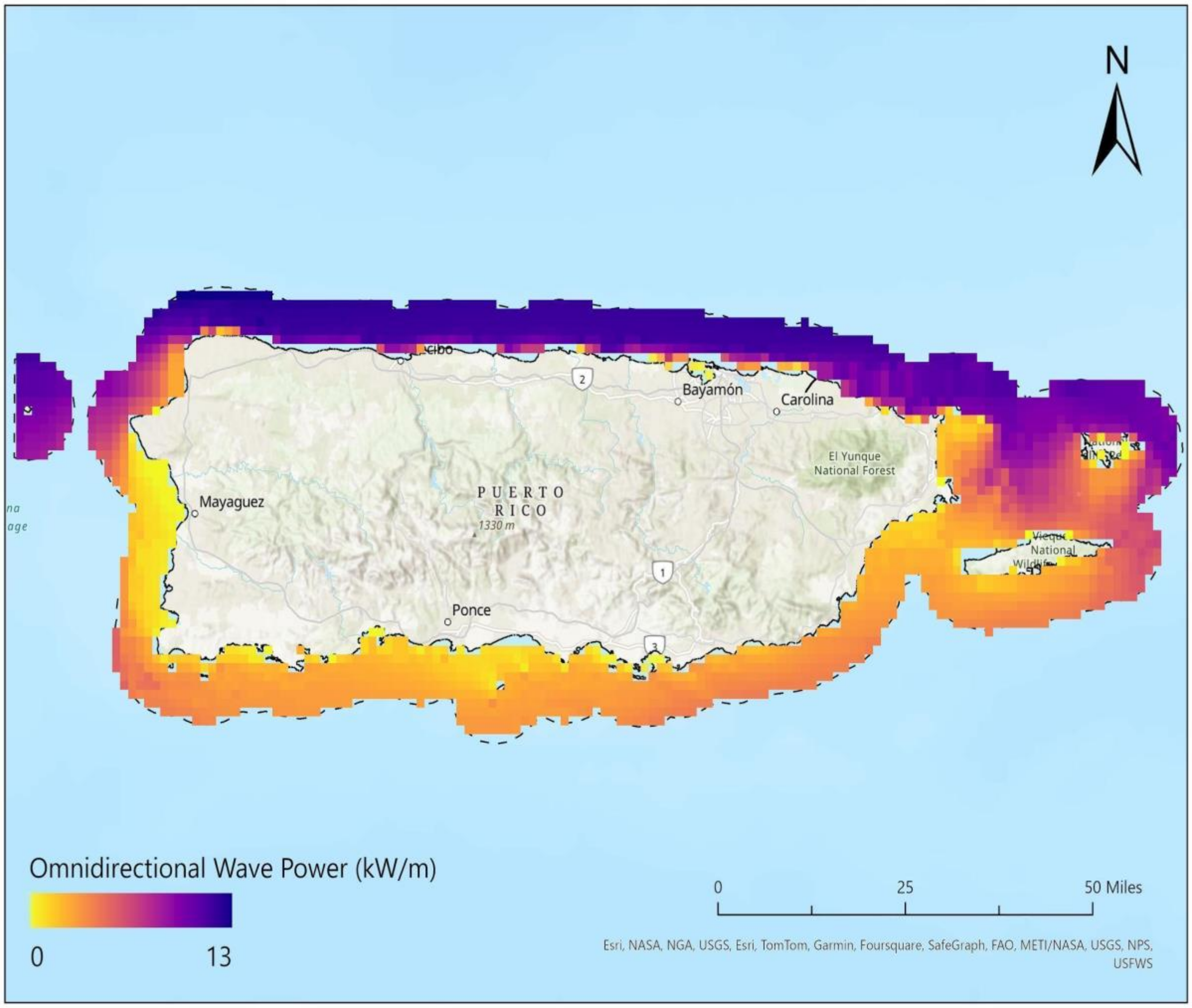


*Figure 4.2 Map of the omnidirectional wave power (kW/m).*

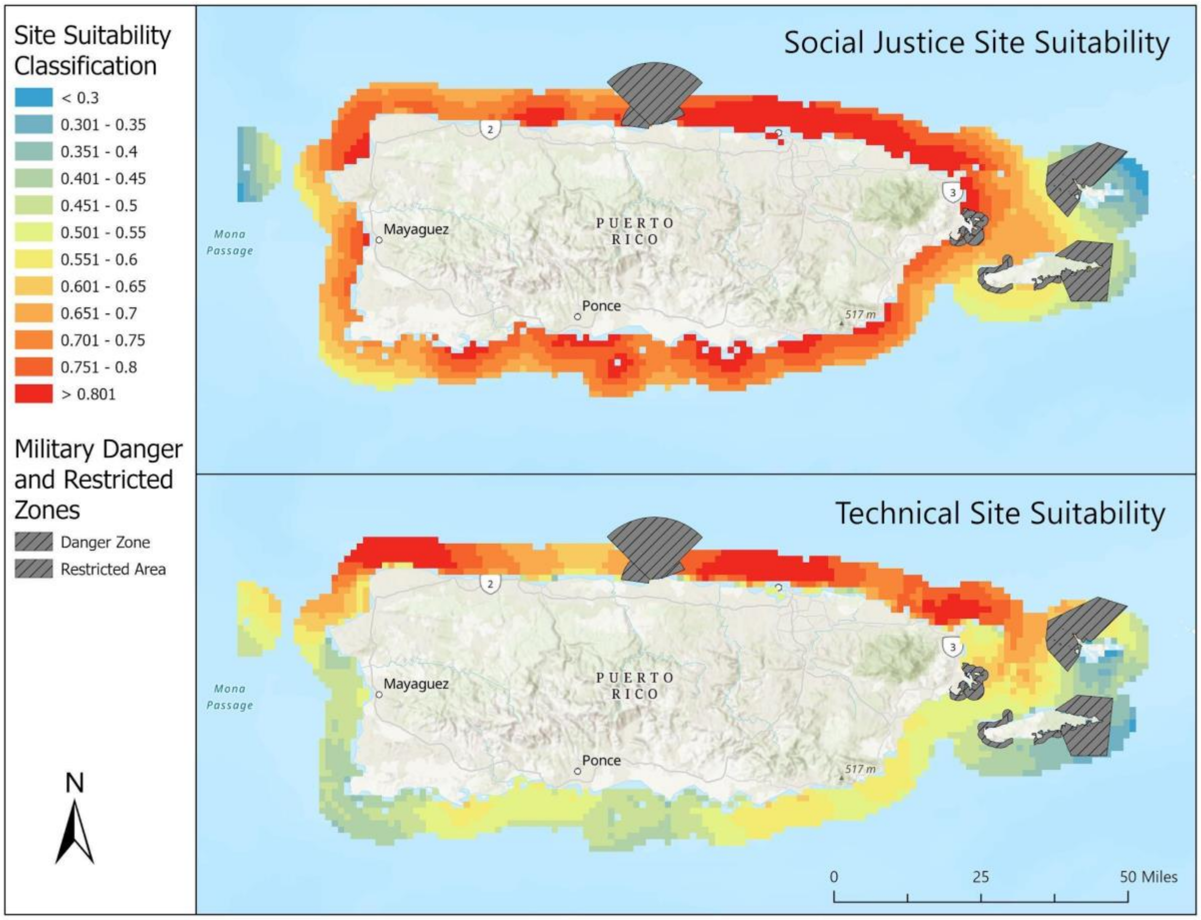


*Figure 4.3 This map displays the social justice and technical site suitability overlays. The social justice map analysis used data layers: wave power, city proximity, port proximity, electric transmission line proximity, and Justice40 social justice factors. The technical map analysis used data layers: wave power, city proximity, port proximity, and electric transmission line proximity. Military danger and restricted zones are overlaid on both maps. The legend applies for both maps. Sites with values greater than 0.751 are classified as highly suitable, while sites with values less than 0.45 are classified as unsuitable.*

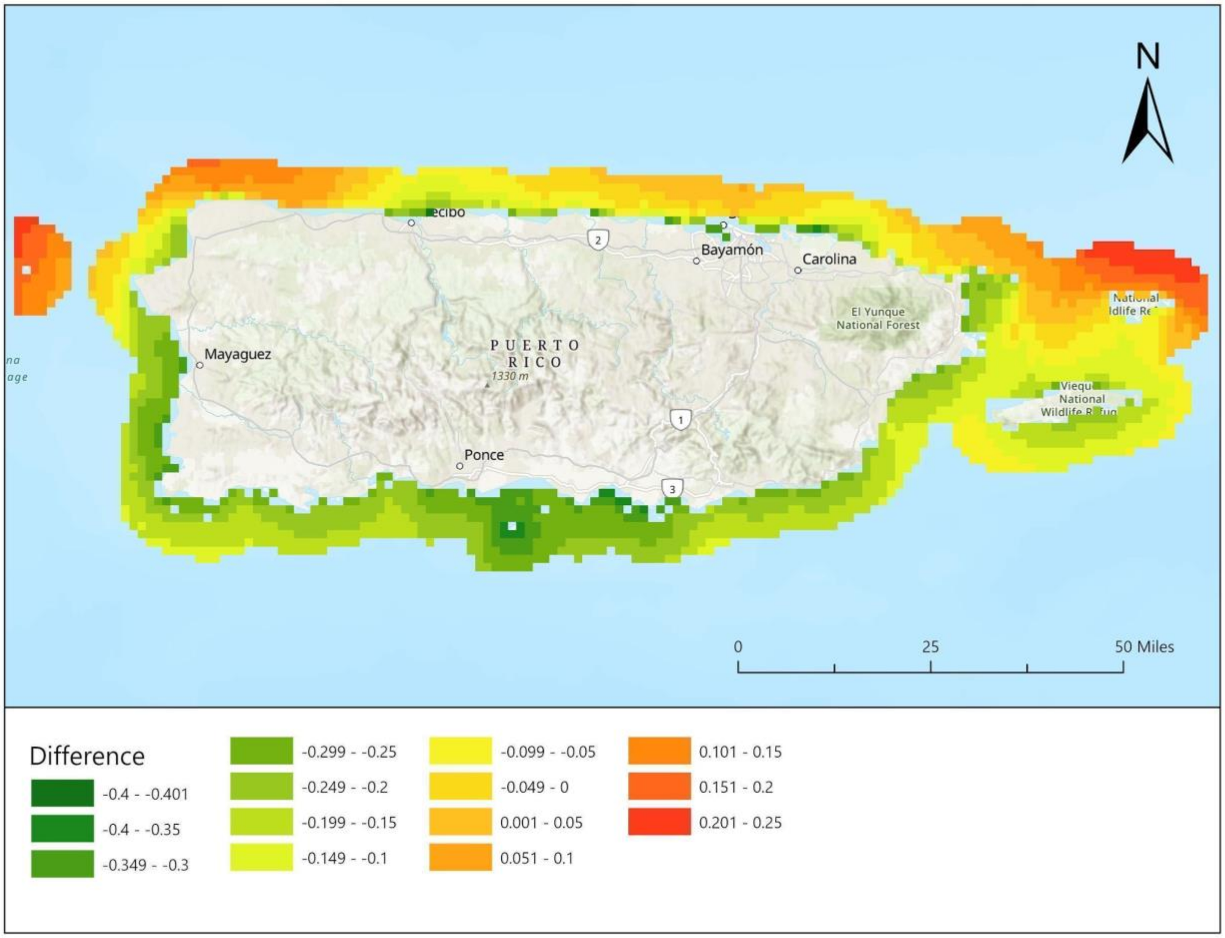


*Figure 4.4 Map showing the difference between technical overlay and social justice overlay. The red values (0.1 through 0.25) favor technical criteria over social justice factors, while the green values (-0.4 through -0.25) favor social justice criteria. The yellow/orange color corresponds to areas similarly valued by both analyses.*

## 4.2 Hawaiʻi Case Study

The criteria weights used during the suitability analyses were created from an AHP analysis (Figure 4.5). The highest weighted criteria were the three energy resources, wave, wind, and solar. The consistency ratio was 1.3%, showing that the criteria matrix was consistent. The solar, wind, and wave energy resource map is displayed in Figure 4.6. There is a strong correlation of wind, wave, and solar energy resources for the study area. The strongest concentration of energy potential is along the north shore of the islands. There is also a small section along the SE tip of the study area and another site off the south coast of Maui. The two output overlay maps are displayed in Figure 4.7: the overlay with social justice criteria and the technical overlay without social justice criteria. The first analysis used these criteria: Justice40 disadvantaged communities, wave energy resource, solar energy resource, wind energy resource, port proximity, and transmission line proximity. The first overlay indicates that there are suitable sites located along the northern part of the study area, however, there are only a few patches of highly suitable areas. One is located to the NE of Lihue, and another to the NE of Maui. The second analysis used these criteria: wave energy resource, solar energy resource, wind energy resource, port proximity, and transmission line proximity. The second overlay displays that there are highly suitable areas along the northern parts of the study site. Additionally, there is a location south of the Big Island that is also classified as highly suitable. The sites with suitability values over 0.751 are considered highly suitable, while those with values less than 0.45 are considered unsuitable. This applies to both maps. The final map of the difference between the technical and social justice map overlays (Figure 4.8) was created using the Raster Calculator tool, to subtract the technical map values from the social justice map values. The map highlights the differences in scores given to sites by each analysis.

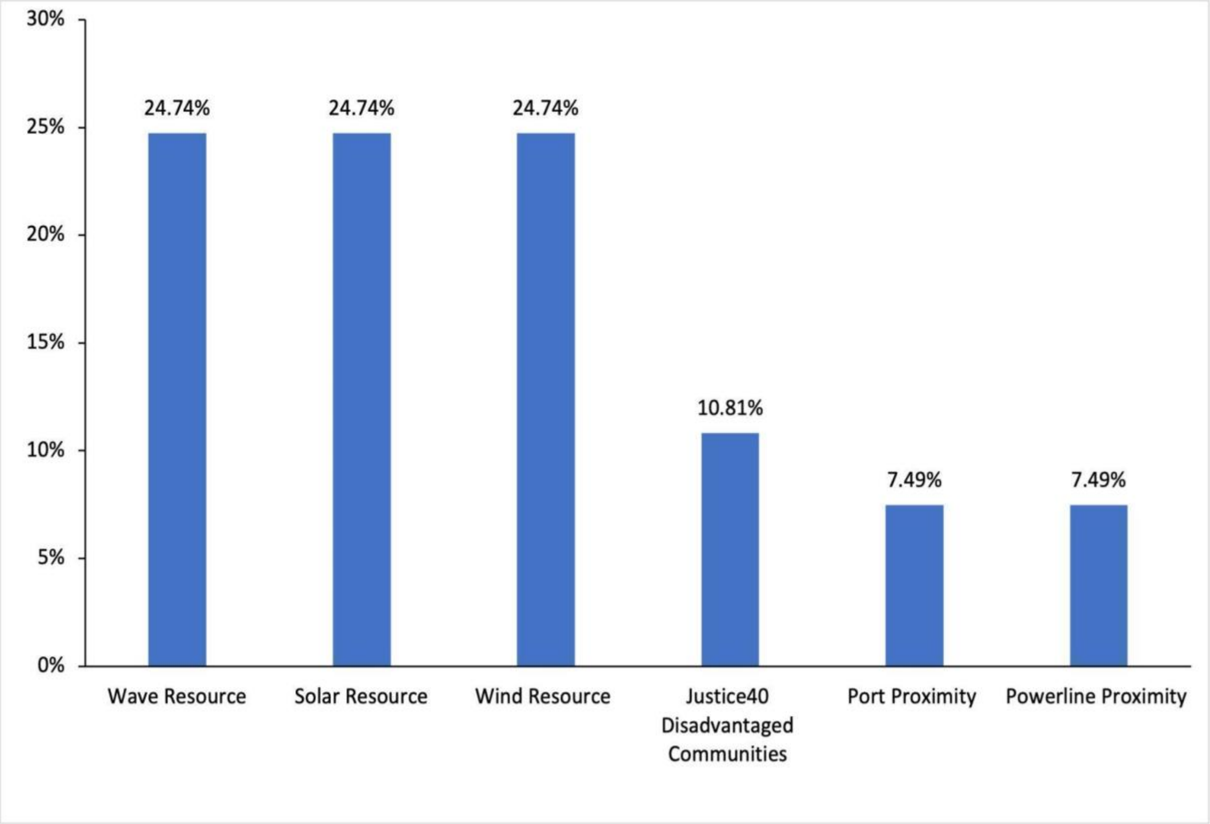


*Figure 4.5 Hawai‘i criteria weightings calculated using the AHP analysis.*

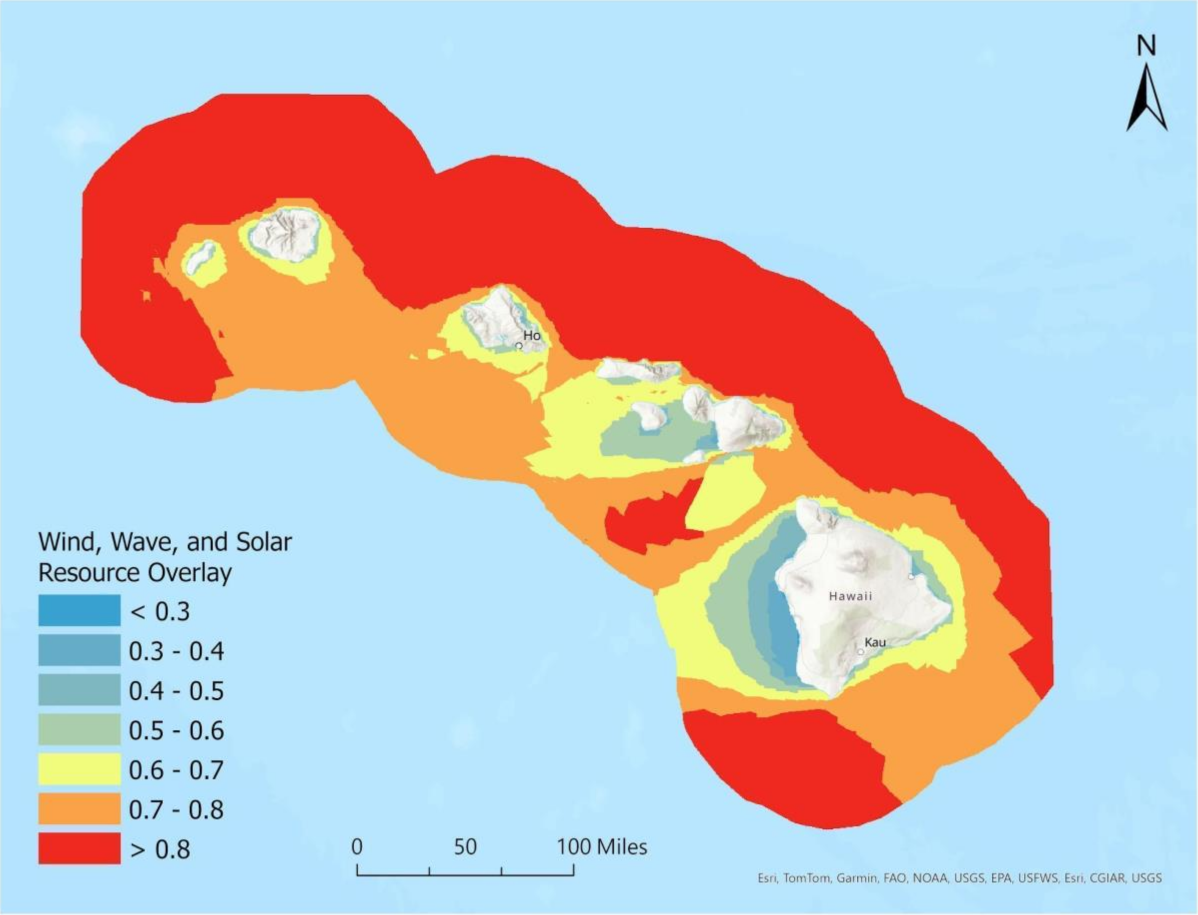


*Figure 4.6 Map of energy resource overlay where PV resource, wind speeds, and omnidirectional wave power were equally weighted.*

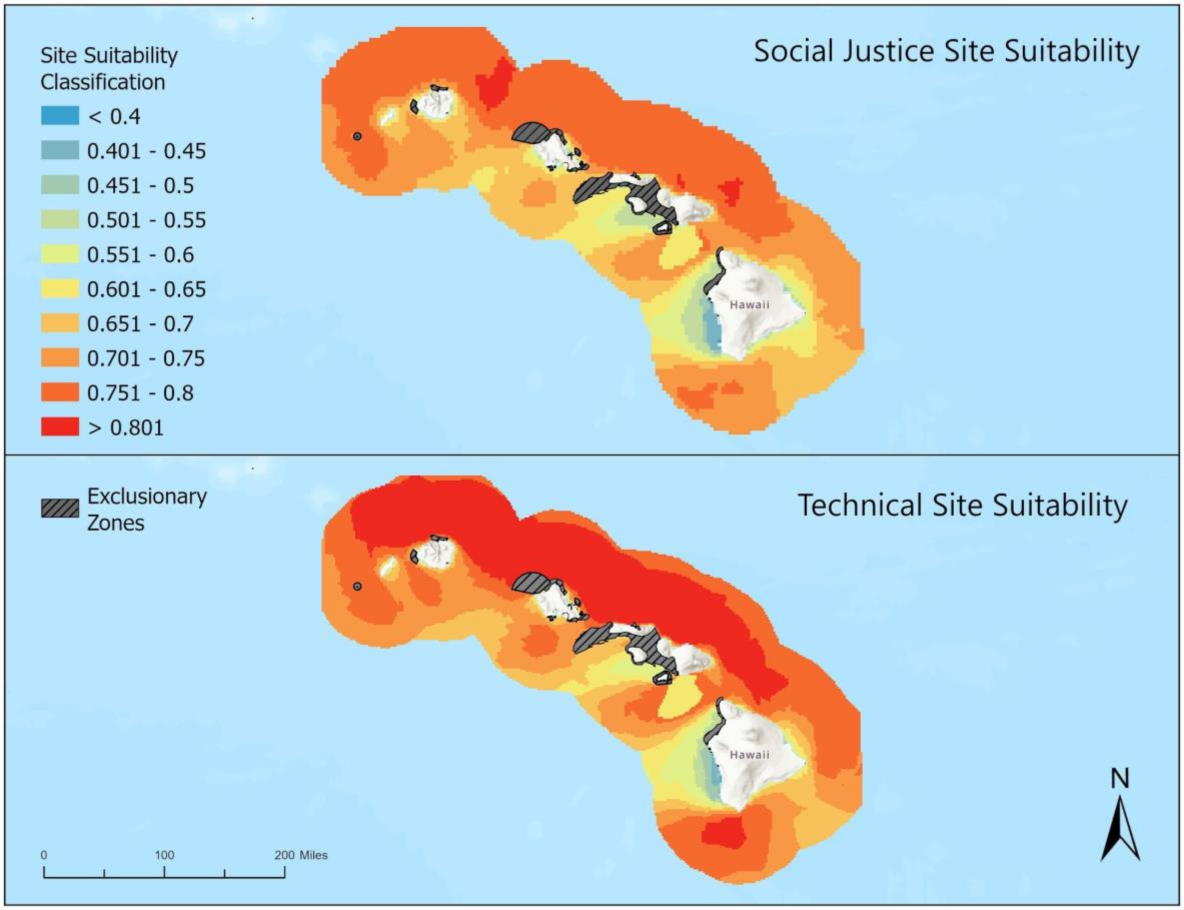


*Figure 4.7 Map of the social justice site suitability overlay and the technical site suitability. The social justice site suitability included all layers for analysis: wave power, solar PV power, wind speeds, transmission line proximity, port proximity, and Justice40 disadvantaged communities. The technical site suitability analysis included all technical and resource layers: wave power, solar PV power, wind speeds, transmission line proximity, and port proximity. The exclusionary zones encompass Marine Protected Areas (MPA) and military danger and restricted zones. The legend applies to both maps. Sites with values greater than 0.751 are classified as highly suitable, while sites with values less than 0.45 are classified as unsuitable.*

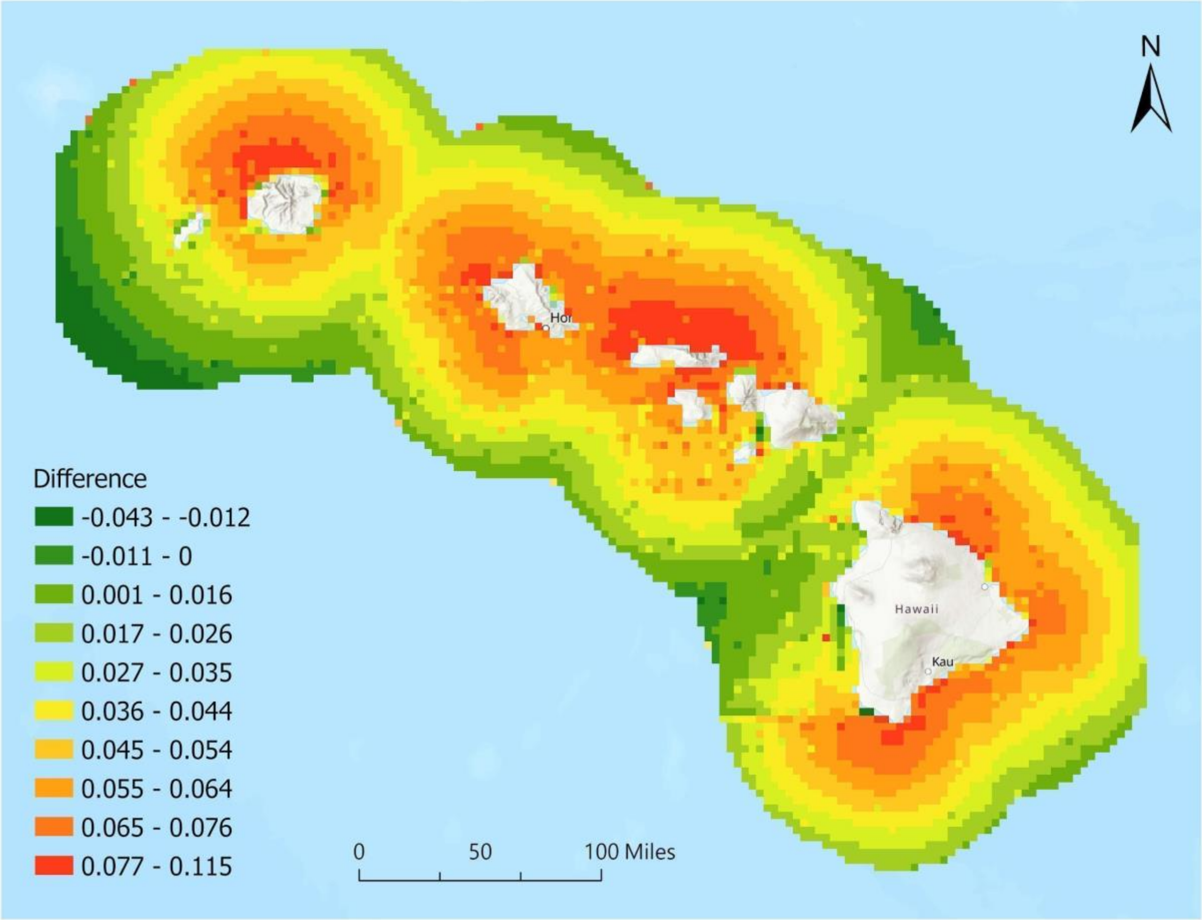


*Figure 4.8 Map of the difference between the technical site suitability overlay and the social justice overlay. The red values (0.055 through 0.115) favor technical criteria over social justice factors, while the green values (-0.043 through 0.026) favor social justice criteria. The yellow/orange color corresponds to areas similarly valued by both analyses.*

# 5 Discussion

Results from the Puerto Rico case study indicate that there are highly suitable sites for CSI-WEC deployment that should be further explored, specifically off the northeastern coast and along areas on the southeastern coast. Furthermore, site suitability results reveal that the suitable sites identified with the inclusion of social justice criteria differ from those identified by the technical analysis. Results from Hawaiʻi denote several potential suitable sites for hybrid wind-wave-solar projects surrounding the islands of Hawaiʻi, specifically off the northern coasts. The results of the two case studies demonstrate general similarities, such as favoring the north and northeastern shores. General climate patterns that affect both regions could explain this preference, namely the westerly winds that impact the wind and wave resources. An important difference between the studies is how the addition of social justice criteria impacts the distribution of suitable sites. In Puerto Rico, the inclusion of social justice criteria increases the number of suitable sites, whereas, in Hawaiʻi, it decreases them.

## 5.1 Puerto Rico Study

The technical analysis strongly favors sites with high wave energy resources (Figure 4.3b), thus the suitability map strongly resembles the wave resource map (Figure 4.2). In contrast, including the social justice criteria identifies many more sites surrounding Puerto Rico as highly suitable (Figure 4.3a). The NE corner of the island surrounding San Juan is one of these sites, which interestingly, shows up in both analyses. The analysis with social justice criteria also identifies multiple highly suitable sites along the southern coast that other analyses undervalued (Figure 4.3). The difference map further supports this, indicating that sites on the southern coast scored significantly higher when including the social justice criteria in the analysis. This demonstrates that the inclusion of social justice criteria impacts the results of site suitability analysis by prioritizing sites near communities that are most in need of clean energy investment. If the analysis was conducted using only technical criteria, which is the current standard, these sites would never have been considered for further development. While it is important for minimum technological energy requirements to be met, site selection needs to be moving towards more equitable decisions (Caballero et al., 2023).

Something of interest about the analysis with social justice criteria is that the neighboring islands have very low scores, and this is most likely because most of the islands are uninhabited or have low population counts, thus they have Justice40 data values closer to zero. Including these islands skew the overall analysis toward highly populated places, thus any coastal space of the main island is scored highly relative to the smaller islands. The results indicate that the smaller islands of Culebra and Vieques are not suitable for CSI-WEC projects. For future analyses, narrowing the study area to only encompass the main island of Puerto Rico could provide more variation in the scores around the main island.

Overall, the results provided a successful selection of general CSI-WEC sites in Puerto Rico to further analyze; however, an analysis that focuses solely on the main island would provide more nuanced results. One strength of MCDA analysis methods is to easily narrow down site possibilities, and this was less successful in Puerto Rico because the results heavily favor any locations near the main island. The sites on the southern coast of Puerto Rico are areas that have been reported as suffering from long power outages during storms in unreliable power access in normal conditions (Sotolongo et al., 2021). These sites are scored higher with the addition of social justice criteria, which highlights the ability of the tool to prioritize communities that can benefit most from renewable energy projects.

## 5.2 Hawai‘i Case Study

The northern shores of Hawai‘i exhibit the strongest correlation of the wind, wave, and solar energy resources (Figure 4.6). The technical suitability map is very similar to the energy resource map (Figure 4.7b); however, some differences appear to be related to the technical data. Infrastructure proximity, such as transmission lines or ports, may cause moderately suitable sites on the energy resource map to score higher on the technical suitability map. For example, while the area to the south of Maui was ranked as least suitable on the energy resource map, it was scored as moderately suitable on the technical suitability map. The analysis with social justice criteria yields similar results to the technical suitability results but with lower overall suitability (Figure 4.7a). This is likely due to the classification of the Justice40 data, where locations closer to shore were weighted lower to protect disadvantaged communities. This is supported by the comparison map (Figure 4.8), which demonstrates that the technical suitability map heavily values locations closer to islands, suggesting that the buffer created by the social justice criteria strongly influences the analyses.

Overall, this case study demonstrates the success of GIS-based MCDA methods to assist in making siting decisions. The results identified several suitable sites for hybrid systems located along the northern coasts of the islands. These sites have abundant energy resources and available infrastructure, but they are also far enough from shore to avoid marine spatial use conflicts. Enhancing the results of these analyses would involve adding more marine use or social justice criteria to ensure that sites do not adversely impact native Hawaiian populations.

## 5.3 Case Study Comparison

Both GIS MCDA results highlighted sites that could be further analyzed for the deployment of each marine energy technology. This demonstrates two successful case studies of GIS-based MCDA in the marine energy space. Both studies shared a similarity in that the technical suitability analyses were heavily influenced by the energy resource criteria. The northern and northeastern shores of the islands got the highest scores on the energy resource map, which could be due to the general climatic processes that impact both areas. Puerto Rico and Hawaiʻi are at similar latitudes (between 19-22) where the trade winds play a role in the wind and wave climate.

A key difference between the studies is the impact that adding the social justice criteria had on the results. The three maps of Hawaiʻi look relatively similar, with only small differences between sites scored highly. The maps of Puerto Rico do not look similar. This difference likely arises from the variations in population distribution across each area. The surrounding islands of Puerto Rico, Culebra and Vieques, have very low population numbers. Therefore, areas closer to the main island scored much higher with the inclusion of the social justice criteria. In contrast, the Hawaiian Islands have a population that is less clustered and better distributed. Another difference is that including the Hawaiʻi social justice criteria created a more limited number of highly suitable sites, whereas including the Puerto Rico social justice criteria increased the number of sites. Once more, this difference could be attributed to the variations in population distribution between the islands of the two studies. This difference is also likely due to the way the proximity to Justice40 communities was ranked. In Puerto Rico, closer proximity was ranked higher to prioritize communities that have been underserved, whereas in Hawaiʻi closer proximity was ranked lower in order to protect overburdening native communities. These results indicate that how social data is used and weighted have a significant impact on the results. For this reason, the different criteria included in site selection analysis should be very thoroughly outlined and discussed. The site selection process is an important time when prospective stakeholders should be approached in order to hear local concerns and questions that could be addressed with data during site selection.

It’s important to note that, historically, energy projects with negative impacts, such as pollution risks, have often been disproportionately placed in socially vulnerable communities. Care should be taken that these methods are not used to create more injustices. The environmental and social impact of each technology should be carefully considered, and local communities should always be included in planning in order to ensure that their concerns are being heard.

## 5.4 Future Considerations

During this research, one of the greatest limitations was the availability and quality of geospatial data for both study areas. Many studies have highlighted this issue (Flocard et al., 2016; Vasileiou et al., 2017) and something that marine spatial planning, such as the MSP in the EU, is working to address (European Commission, 2022). In both cases, energy resource data is crucial for technical suitability analysis, but the nearshore resolution of wave data is very low. For Puerto Rico, where the CSI-WEC technology is on or near shore, the nearshore wave resource is vital. This type of data is key to further development of site selection tools for CSI-WECs, and marine energy projects in general. Data on the frequency and intensity of storms would also be valuable in identifying locations that most need storm surge protection provided by CSI-WECs. Furthermore, geospatial social data was especially difficult to find, likely leading to the underuse of social data for GIS analysis. The Justice40 dataset is an excellent example of social data that can be very impactful on site selection decisions, which is why it was used for both sites. For example, in Hawaiʻi it is important to acknowledge the right of native Hawaiians to their native lands and cultural practices, thus data representing culturally significant areas and areas essential to cultural practices could be incorporated to make siting decisions that avoid these areas. There is also a general lack of geospatial data classifying marine activities throughout marine spaces. For example, locating marine areas that are used by native Hawaiians for fishing would be invaluable to add to site selection analysis. These types of marine social data would help proactively address marine use conflicts and enable more transparent and equitable project development moving forward.

# 6 Conclusion

This study demonstrated how GIS-based MCDA methods optimize marine energy site selection while also ensuring equitable and just development. Results from Puerto Rico and Hawai‘i identified highly suitable areas around the islands for future exploration and development. Moreover, the results of the suitability analysis with social justice criteria highlighted different suitable locations than the suitability analysis with technical and energy resources, underlining the importance of considering socioeconomic factors in the decision-making process. The GIS-based MCDA methods applied in this study provide an efficient tool for marine energy site selection, enabling the consideration of a wide range of criteria across various technologies. Additionally, the flexibility to adjust criteria based on specific site conditions and energy device requirements enhances the adaptability of these methods. Site selection is a lengthy part of a project timeline; thus, this tool can streamline projects and accelerate the deployment of marine renewable energy devices. This efficiency is essential for scaling up the world’s renewable energy portfolio to meet global climate targets; however, it is also imperative to prioritize equity and environmental justice.

# 7 Bibliography

Abbasi, S. A., & Abbasi, N. (2000). The likely adverse environmental impacts of renewable energy sources. *Applied Energy*, *65*(1), 121–144. https://doi.org/10.1016/S0306-2619(99)00077-X

Ahn. S, Neary, V.S., Nabi, M., He, R. (2022). A framework for feasibility-level validation of high-resolution wave hindcast models, *Ocean Engineering.*, *263*, 112193. https://doi.org/10.1016/j.oceaneng.2022.112193

Ali, U., Shamsi, M.H., Bohacek, M., Purcell, K., Hoare, C., Mangina, E., & O'Donnell, J. (2020). A data-driven approach for multi-scale GIS-based building energy modeling for analysis, planning and support decision making. *Applied Energy*, *279*, 115834. https://doi.org/10.1016/j.apenergy.2020.115834

Allahdadi, M. N., He, R., Ahn, S., Chartrand, C., & Neary, V. S. (2021). Development and calibration of a high-resolution model for the Gulf of Mexico, Puerto Rico, and the U.S. Virgin Islands: Implication for wave energy resource characterization. *Ocean Engineering*, *235*, 109304. https://doi.org/10.1016/j.oceaneng.2021.109304

Atmaca, E., & Basar, H. B. (2012). Evaluation of power plants in Turkey using Analytic Network Process (ANP). *Energy*, *44*(1), 555–563. https://doi.org/10.1016/j.energy.2012.05.046

Azzellino, A., Lanfredi, C., Riefolo, L., De Santis, V., Contestabile, P., & Vicinanza, D. (2019). Combined Exploitation of Offshore Wind and Wave Energy in the Italian Seas: A Spatial Planning Approach. *Frontiers in Energy Research*, *7*. https://www.frontiersin.org/articles/10.3389/fenrg.2019.00042

Azzellino, A., Ferrante, V., Kofoed, J. P., Lanfredi, C., & Vicinanza, D. (2013). Optimal siting of offshore wind-power combined with wave energy through a marine spatial planning approach. *International Journal of Marine Energy*, *3–4*, e11–e25. https://doi.org/10.1016/j.ijome.2013.11.008

Baban, S. M. J., & Parry, T. (2001). Developing and applying a GIS-assisted approach to locating wind farms in the UK. *Renewable Energy*, *24*(1), 59–71. https://doi.org/10.1016/S0960-1481(00)00169-5

Backer, H. (2011). Transboundary maritime spatial planning: A Baltic Sea perspective. *Journal of Coastal Conservation*, *15*(2), 279–289. https://doi.org/10.1007/s11852-011-0156-1

Barreto-Orta M, Instituto de Investigación y Planificación Costera de PR (CoRePI). (2021, April 15). *El estado de costa en Puerto Rico:* ArcGIS StoryMaps. https://storymaps.arcgis.com/stories/bc4b7c14ec904571a47175129f6baba8

Bashir, M. B. A. (2022). Principle Parameters and Environmental Impacts that Affect the Performance of Wind Turbine: An Overview. *Arabian Journal for Science and Engineering*, *47*(7), 7891–7909. https://doi.org/10.1007/s13369-021-06357-1

Bennui, A., Rattanamanee, P., Puetpaiboon, U., Phukpattaranont, P., & Chetpattananondh, K. (2007). Site selection for large wind turbine using GIS. *PSU-UNS International Conference on Engineering and Environment*, 561–566.

Blair, Nate, Robin Burton, Murali Baggu, Haiku Sky, Tom Harris, Clayton Barrows, Vahan Gevorgian, Jeremy Keen, Manajit Sengupta, Cameron Weiner, James Morris, Paritosh Das, James Elsworth, Prateek Joshi, Joseph McKinsey, Surya Dhulipala, Matthew Lave, Amanda Wachtel, Marcelo Elizondo, Xiaoyuan Fan, Patrick Maloney, Vishvas Chalishazar, Peter Cappers, Sydney Forrester, Jeff Deason, Margaret Pigman, Lawrence Paul Lewis, John Murphy, Ben Ollis, Thomaz Carvalhaes, Harvey Cutler, Martin Shields, and Michele Chait. (2023). PR100 One-Year Progress Summary Report: Preliminary Modeling Results and High-Resolution Solar and Wind Data Sets. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-85018. https://www.nrel.gov/docs/fy2023/85018.pdf.

Caballero, M. D., Gunda, T., & McDonald, Y. J. (2023). Energy justice & coastal communities: The case for Meaningful Marine Renewable Energy Development. *Renewable and Sustainable Energy Reviews*, *184*, 113491. https://doi.org/10.1016/j.rser.2023.113491

Carmichael, C. E., & McDonough, M. H. (2019). Community Stories: Explaining Resistance to Street Tree-Planting Programs in Detroit, Michigan, USA. *Society & Natural Resources*, *32*(5), 588–605. https://doi.org/10.1080/08941920.2018.1550229

Carr-Harris, A., & Lang, C. (2019). Sustainability and tourism: The effect of the United States' first offshore wind farm on the vacation rental market. *Resource and Energy Economics*, *57*, 51–67. https://doi.org/10.1016/j.reseneeco.2019.04.003

City and County of Honolulu - Climate Change Commission. (2018). *Climate Change Brief.* https://static1.squarespace.com/static/5e3885654a153a6ef84e6c9c/t/64374370c0631e3ac922692a/1681343347345/Climate+Change+Brief+2023.pdf

Climate and Economics Justice Screening Tool (CEJST). Washington, D.C.: Council on Environmental Quality, 2022. Available: https://screeningtool.geoplatform.gov/en/methodology#3/33.47/-97.5 (Accessed June 18, 2023).

Cradden, L., Kalogeri, C., Barrios, I. M., Galanis, G., Ingram, D., & Kallos, G. (2016). Multi-criteria site selection for offshore renewable energy platforms. *Renewable Energy*, *87*, 791–806. https://doi.org/10.1016/j.renene.2015.10.035

Defne, Z., Haas, K. A., & Fritz, H. M. (2011). GIS based multi-criteria assessment of tidal stream power potential: A case study for Georgia, USA. *Renewable and Sustainable Energy Reviews*, *15*(5), 2310–2321. https://doi.org/10.1016/j.rser.2011.02.005

Deveci, M., Cali, U., & Pamucar, D. (2021). Evaluation of criteria for site selection of solar photovoltaic (PV) projects using fuzzy logarithmic additive estimation of weight coefficients. *Energy Reports*, *7*, 8805–8824. https://doi.org/10.1016/j.egyr.2021.10.104

U.S. Department of Energy (DOE). 2022. Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100). Golden, CO: National Renewable Energy Laboratory. Energy.gov. https://www.energy.gov/gdo/puerto-rico-grid-resilience-and-transitions-100-renewable-energy-study-pr100

U.S. Department of Energy (DOE). 2021. Hybrid Energy Systems: Opportunities for Coordinated Research. Golden, CO: National Renewable Energy Laboratory. DOE/GO-102021-5447. https://www.nrel.gov/docs/fy21osti/77503.pdf

Diggon, S., Butler, C., Heidt, A., Bones, J., Jones, R., & Outhet, C. (2021). The Marine Plan Partnership: Indigenous community-based marine spatial planning. *Marine Policy*, *132*, 103510. https://doi.org/10.1016/j.marpol.2019.04.014

European Parliament, Council of the European Union (2014). 'Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning' *Office Journal* L257 https://eur-lex.europa.eu/eli/dir/2014/89/oj

Draxl, C., Clifton, A., Hodge, B-M., McCain, J. (2015). The Wind Integration National Dataset (WIND) Toolkit. Appl Energy, http://dx.doi.org/10.1016/j.apenergy.2015.03.121

Drehobl, A., Ross, L., and Ayala, R. 2020. *How High Are Household Energy Burdens?* Washington, DC: American Council for an Energy-Efficient Economy.

Earth Economics. The Sociocultural Significance of Pacific Salmon to Tribes and First Nations. 2021. https://static1.squarespace.com/static/561dcdc6e4b039470e9afc00/t/60c257dd24393c6a6c1bee54/1623349236375/The-Sociocultural-Significance-of-Salmon-to-Tribes-and-First-Nations.pdf

Effat, H. A., & El-Zeiny, A. M. (2022). Geospatial modeling for selection of optimum sites for hybrid solar-wind energy in Assiut Governorate, Egypt. *The Egyptian Journal of Remote Sensing and Space Science*, *25*(2), 627–637. https://doi.org/10.1016/j.ejrs.2022.03.005

Ehler, C., & Douvere, F. (2009). Marine Spatial Planning: A step-by-step approach toward ecosystem-based management. Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. [99pp.]. https://doi.org/10.25607/OBP-43

Elgabiri, M., Palmer, D., Al Buflasa, H., & Thomson, M. (2021). Offshore wind energy potential for Bahrain via multi-criteria evaluation. *Wind Engineering*, *45*(4), 838–856. https://doi.org/10.1177/0309524X20925399

ESRI 2011. ArcGIS Desktop: Release 10.8 Redlands, CA: Environmental Systems Research Institute.

European Union: European Commission, Report from the Commission to the European Parliament and the Council: Outlining the progress made in implementing Directive 2014/89/EU establishing a framework for maritime spatial planning, 3rd of May 2022, COM(2022) 185 final, available at https://eur-lex.europa.eu/legal content/EN/TXT/HTML/?uri=CELEX%3A52022DC0185

The White House. (2021) "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/

Flocard, F., Ierodiaconou, D., & Coghlan, I. R. (2016). Multi-criteria evaluation of wave energy projects on the south-east Australian coast. *Renewable Energy*, *99*, 80–94. https://doi.org/10.1016/j.renene.2016.06.036

Gideon, R. A., & Bou-Zeid, E. (2021). Collocating offshore wind and wave generators to reduce power output variability: A Multi-site analysis. *Renewable Energy*, *163*, 1548–1559. https://doi.org/10.1016/j.renene.2020.09.047

Gittman, R. K., Fodrie, F. J., Popowich, A. M., Keller, D. A., Bruno, J. F., Currin, C. A., Peterson, C. H., & Piehler, M. F. (2015). Engineering away our natural defenses: An analysis of shoreline hardening in the US. *Frontiers in Ecology and the Environment*, *13*(6), 301–307. https://doi.org/10.1890/150065

Gopnik, M., Fieseler, C., Cantral, L., McClellan, K., Pendleton, L., Crowde, L. (2012). Coming to the table: Early stakeholder engagement in marine spatial planning. *Marine Policy*, *36*(5), 1139–1149. https://doi.org/10.1016/j.marpol.2012.02.012

Hall, P. K., Morgan, W., & Richardson, J. (2022). Land Use Conflicts Between Wind and Solar Renewable Energy and Agriculture Uses.

Hartman L. (2023) *Wind Turbines: The Bigger, the Better*. Energy.Gov. https://www.energy.gov/eere/articles/wind-turbines-bigger-better

Hawaiʻi Clean Energy Initiative. (n.d.). *Hawaiʻi State Energy Office*. Retrieved February 13, 2024, from https://energy.hawaii.gov/hawaii-clean-energy-initiative/

Hawai‘i Climate Change Mitigation and Adaptation Commission. (2017). Hawai‘i Sea Level Rise Vulnerability and Adaptation Report. Prepared by Tetra Tech, Inc. and the State of Hawai‘i Department of Land and Natural Resources, Office of Conservation and Coastal Lands, under the State of Hawai‘i Department of Land and Natural Resources Contract No: 64064

Hildenbrand, K. (2014). *Wave-Energy Devices Might Affect the Natural Environment*. Oregon State University. https://seagrant.oregonstate.edu/sites/seagrant.oregonstate.edu/files/sgpubs/onlinepubs/g14001.pdf

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C., & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, *111*(9), 3292–3297. https://doi.org/10.1073/pnas.1222469111

Hosseinzadeh, S., Etemad-Shahidi, A., & Stewart, R. A. (2023). Site Selection of Combined Offshore Wind and Wave Energy Farms: A Systematic Review. *Energies*, *16*(4), 2074. https://doi.org/10.3390/en16042074

Houser, T., & Marsters, P. (2017). America’s Biggest Blackout. *Rhodium Group*. Retrieved July 13, 2023, from https://rhg.com/research/americas-biggest-blackout-2/

Ilbahar, E., Cebi, S., & Kahraman, C. (2019). A state-of-the-art review on multi-attribute renewable energy decision making. *Energy Strategy Reviews*, *25*, 18–33. https://doi.org/10.1016/j.esr.2019.04.014

IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

Janke, J. R. (2010). Multicriteria GIS modeling of wind and solar farms in Colorado. *Renewable Energy*, *35*(10), 2228–2234. https://doi.org/10.1016/j.renene.2010.03.014

Jessel, S., Sawyer, S., & Hernández, D. (2019). Energy, Poverty, and Health in Climate Change: A Comprehensive Review of an Emerging Literature. *Frontiers in Public Health*, *7*, 357. https://doi.org/10.3389/fpubh.2019.00357

Kaldellis, J. K., Apostolou, D., Kapsali, M., & Kondili, E. (2016). Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. *Renewable Energy*, *92*, 543–556. https://doi.org/10.1016/j.renene.2016.02.018

Kamranzad, B., & Hadadpour, S. (2020). A multi-criteria approach for selection of wave energy converter/location. *Energy*, *204*, 117924. https://doi.org/10.1016/j.energy.2020.117924

Kocabaldir, C., & Yücel, M. A. (2020). GIS-Based Multi-Criteria Decision Analysis of Site Selection for Photovoltaic Power Plants in Çanakkale Province. *International Journal of Environment and Geoinformatics*, *7*(3), 347–355. https://doi.org/10.30897/ijegeo.689570

Kokal, A. (2020, July 14). Connecting Past to Present: Confronting Environmental Racism and Social Injustice in Hawaii. *Climate-XChange*. https://climate-xchange.org/2020/07/14/connecting-past-to-present-confronting-environmental-racism-and-social-injustice-in-hawaii/

Kilcher, L., Green, R., Hotchkiss, E., Stark, G., Salmon, A.A., Hill, K. 2021. Igiugig Site Visit Report. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-79607. https://www.nrel.gov/docs/fy22osti/79607.pdf.

Kilcher, L., Fogarty, M., and Lawson, M. 2021. Marine Energy in the United States: An Overview of Opportunities. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-78773. https://www.nrel.gov/docs/fy21osti/78773.pdf.

Kyne, D., & Bolin, B. (2016). Emerging Environmental Justice Issues in Nuclear Power and Radioactive Contamination. *International Journal of Environmental Research and Public Health*, *13*(7), 700. https://doi.org/10.3390/ijerph13070700

Lee, A. H. I., Chen, H. H., & Kang, H.-Y. (2017). A conceptual model for prioritizing dam sites for tidal energy sources. *Ocean Engineering*, *137*, 38–47. https://doi.org/10.1016/j.oceaneng.2017.03.039

Lee, J., & Byrne, J. (2019). Expanding the Conceptual and Analytical Basis of Energy Justice: Beyond the Three-Tenet Framework. *Frontiers in Energy Research*, *7*. https://www.frontiersin.org/articles/10.3389/fenrg.2019.00099

Lemos Bulhões, R., Souza de Santana, E., & Álisson Bandeira Santos, A. (2020). Use of Analytic Hierarchy Process for Wind Farm Installation Region Prioritization–Case Study. *Energies*, *13*(9), Article 9. https://doi.org/10.3390/en13092284

Leong, J.-A., J. J. Marra, M. L. Finucane, T. Giambelluca, M. Merrifield, S. E. Miller, J. Polovina, E. Shea, M. Burkett, J. Campbell, P. Lefale, F. Lipschultz, L. Loope, D. Spooner, and B. Wang, 2014: Ch. 23: Hawai‘i and U.S. Affiliated Pacific Islands. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 537-556. doi:10.7930/J0W66HPM.

Leung, D. Y. C., & Yang, Y. (2012). Wind energy development and its environmental impact: A review. *Renewable and Sustainable Energy Reviews*, *16*(1), 1031–1039. https://doi.org/10.1016/j.rser.2011.09.024

Li, N., García-Medina, G., Cheung, K. F., & Yang, Z. (2021). Wave energy resources assessment for the multi-modal sea state of Hawaii. *Renewable Energy*, *174*, 1036–1055. https://doi.org/10.1016/j.renene.2021.03.116

Lopez, A, Roberts, B, Heimiller, D, Blair, N, & Porro, G. (2012). U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. United States. https://doi.org/10.2172/1047328

Mahdy, M., & Bahaj, A. S. (2018). Multi criteria decision analysis for offshore wind energy potential in Egypt. *Renewable Energy*, *118*, 278–289. https://doi.org/10.1016/j.renene.2017.11.021

McGill, E. (2016). *Dammed Societies: Effects of Dams on Native Americans in the Columbia River Basin*. [Capstone Project, Carroll College]. https://scholars.carroll.edu/server/api/core/bitstreams/0ca1cb8d-0359-4872-a52d-01c91c4e2b91/content

Mendoza, E., Lithgow, D., Flores, P., Felix, A., Simas, T., & Silva, R. (2019). A framework to evaluate the environmental impact of OCEAN energy devices. *Renewable and Sustainable Energy Reviews*, *112*, 440–449. https://doi.org/10.1016/j.rser.2019.05.060

Miller, L. M., & Kleidon, A. (2016). Wind speed reductions by large-scale wind turbine deployments lower turbine efficiencies and set low generation limits. *Proceedings of the*

*National Academy of Sciences*, *113*(48), 13570–13575. https://doi.org/10.1073/pnas.1602253113

Mohai, P., Pellow, D., & Roberts, J. T. (2009). Environmental Justice. *Annual Review of Environment and Resources*, 34, 405–430. https://doi.org/10.1146/annurev-environ-082508-094348

Moradi, S., Yousefi, H., Noorollahi, Y., & Rosso, D. (2020). Multi-criteria decision support system for wind farm site selection and sensitivity analysis: Case study of Alborz Province, Iran. *Energy Strategy Reviews*, *29*, 100478. https://doi.org/10.1016/j.esr.2020.100478

Mueller, M., & Wallace, R. (2008). Enabling science and technology for marine renewable energy. *Energy Policy*, *36*(12), 4376–4382.

Murphy, P., Lundquist, J. K., & Fleming, P. (2020). How wind speed shear and directional veer affect the power production of a megawatt-scale operational wind turbine. *Wind Energy Science*, *5*(3), 1169–1190. https://doi.org/10.5194/wes-5-1169-2020

NOAA, (2023) What is the EEZ? National Ocean Service website, https://oceanservice.noaa.gov/facts/eez.html accessed December 4,

Nobre, A., Pacheco, M., Jorge, R., Lopes, M. F. P., & Gato, L. M. C. (2009). Geo-spatial multi-criteria analysis for wave energy conversion system deployment. *Renewable Energy*, *34*(1), 97–111. https://doi.org/10.1016/j.renene.2008.03.002

Office for Coastal Management, 2024a: AIS Vessel Transit Counts 2022, https://www.fisheries.noaa.gov/inport/item/69555.

Office for Coastal Management, 2023a: Coastal Populated Places, https://www.fisheries.noaa.gov/inport/item/66114

Office of National Marine Sanctuaries, 2024b: Marine Protected Areas (MPA) Inventory 2023-2024, https://www.fisheries.noaa.gov/inport/item/69506.

Office for Coastal Management, 2023b: Principal Ports, https://www.fisheries.noaa.gov/inport/item/56124

Office of Energy Efficiency & Renewable Energy. *WINDExchange: Wind Energy Projects and Shadow Flicker*. (n.d.). Energy.gov. https://windexchange.energy.gov/projects/shadow-flicker

Office of Legacy Management. *What is Environmental Justice?* (n.d.). Energy.gov. https://www.energy.gov/lm/what-environmental-justice

Olsen, E., Fluharty, D., Hoel, A. H., Hostens, K., Maes, F., & Pecceu, E. (2014). Integration at the Round Table: Marine Spatial Planning in Multi-Stakeholder Settings. *PLOS ONE*, *9*(10), e109964. https://doi.org/10.1371/journal.pone.0109964

Outka, U. (2012). Environmental Justice Issues in Sustainable Development: Environmental Justice in the Renewable Energy Transition. *Journal of Environmental and Sustainability Law*, *19*(1), 60.

Peters, J. L., Remmers, T., Wheeler, A. J., Murphy, J., & Cummins, V. (2020). A systematic review and meta-analysis of GIS use to reveal trends in offshore wind energy research and offer insights on best practices. *Renewable and Sustainable Energy Reviews*, *128*, 109916. https://doi.org/10.1016/j.rser.2020.109916

Pietri, G. (2017, November 30). *Neglect, Corruption Left Puerto Rico's Power Grid Ripe for Failure, Observers Say*. Voa News. https://www.voanews.com/a/experts-say-neglect-corruption-left-puerto-rico-power-grid-ripe-for-failure/4144129.html

Polagye, B. and C. Bassett. 2020. Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 66-85). doi:10.2172/1633082

Preziuso D., & Orrell A. (2022). A Framework for Characterizing the Risk of Ice Fall and Ice Throw from Small Wind Turbines. Pacific Northwest National Lab. https://www.pnnl.gov/sites/default/files/media/file/Small%20Wind%20Icing%20Framework%20-%20PNNL-33214.pdf

Puerto Rico Climate Change Council (PRCCC). 2013. State of Puerto Rico's Climate 2010-2013 Executive Summary. Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. ELECTRONIC VERSION. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, Office of Ocean and Coastal Resource Management (NOAA-OCRM). San Juan, PR: pp. 27

Randell, H., & Curley, A. (2023). Dams and tribal land loss in the United States. *Environmental Research Letters*, *18*(9), 094001. https://doi.org/10.1088/1748-9326/acd268

Rose, S., Jaramillo, P., Small, M. J., Grossmann, I., & Apt, J. (2012). Quantifying the hurricane risk to offshore wind turbines. *Proceedings of the National Academy of Sciences*, *109*(9), 3247–3252. https://doi.org/10.1073/pnas.1111769109

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *Decision Making by the Analytic Hierarchy Process: Theory and Applications*, *48*(1), 9–26. https://doi.org/10.1016/0377-2217(90)90057-I

Saidur, R., Rahim, N. A., Islam, M. R., & Solangi, K. H. (2011). Environmental impact of wind energy. *Renewable and Sustainable Energy Reviews*, *15*(5), 2423–2430. https://doi.org/10.1016/j.rser.2011.02.024

Shao, M., Han, Z., Sun, J., Xiao, C., Zhang, S., & Zhao, Y. (2020). A review of multi-criteria decision making applications for renewable energy site selection. *Renewable Energy*, *157*, 377–403. https://doi.org/10.1016/j.renene.2020.04.137

Smith, E., & Klick, H. (2008). Explaining NIMBY opposition to wind power.

Smythe, T. C., & McCann, J. (2018). Lessons learned in marine governance: Case studies of marine spatial planning practice in the U.S. *Marine Policy*, *94*, 227–237. https://doi.org/10.1016/j.marpol.2018.04.019

Sotolongo, M., Kuhl, L., & Baker, S. H. (2021). Using environmental justice to inform disaster recovery: Vulnerability and electricity restoration in Puerto Rico. *Environmental Science & Policy*, *122*, 59–71. https://doi.org/10.1016/j.envsci.2021.04.004

Sovacool, B. K. (2009). Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy*, *37*(6), 2241–2248. Scopus. https://doi.org/10.1016/j.enpol.2009.02.011

Sweet, W.V., Hamlington, B.D., Kopp, R.E., and Weaver, C.P., (2022). Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. (National Oceanic and Atmospheric Administration, p. 111. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

Taoufik, M., & Fekri, A. (2021). GIS-based multi-criteria analysis of offshore wind farm development in Morocco. *Energy Conversion and Management: X*, *11*, 100103. https://doi.org/10.1016/j.ecmx.2021.100103

Tercan, E., Tapkın, S., Latinopoulos, D., Dereli, M. A., Tsiropoulos, A., & Ak, M. F. (2020). A GIS-based multi-criteria model for offshore wind energy power plants site selection in both sides of the Aegean Sea. *Environmental Monitoring and Assessment*, *192*(10), 652. https://doi.org/10.1007/s10661-020-08603-9

Tegou, L.-I., Polatidis, H., & Haralambopoulos, D. (2010). Environmental management framework for wind farm siting: Methodology and case study. *Journal of Environmental Management*, *91*, 2134–2147. https://doi.org/10.1016/j.jenvman.2010.05.010

UNESCO. (2023, September 18). MSP Roadmap. https://www.mspglobal2030.org/msp-roadmap/msp-around-the-world/americas/usa/

U.S. Energy Information Administration (EIA). (2023b, June 30). Electricity Explained Electricity in the United States. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

U.S. Energy Information Administration (EIA). (2023a, March 16). Hawaii State Profile. Retrieved February 13, 2024, from https://www.eia.gov/state/analysis.php?sid=HI#3

Vagiona, D., & Kamilakis, M. (2018). Sustainable Site Selection for Offshore Wind Farms in the South Aegean—Greece. *Sustainability*, *10*(3), 749. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su10030749

Vasileiou, M., Loukogeorgaki, E., & Vagiona, D. G. (2017). GIS-based multi-criteria decision analysis for site selection of hybrid offshore wind and wave energy systems in Greece. *Renewable and Sustainable Energy Reviews*, *73*, 745–757. https://doi.org/10.1016/j.rser.2017.01.161

Vicinanza, D., Lauro, E. D., Contestabile, P., Gisonni, C., Lara, J. L., & Losada, I. J. (2019). Review of innovative harbor breakwaters for wave-energy conversion. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *145*(4), 03119001.

Viviano, A., Naty, S., Foti, E., Bruce, T., Allsop, W., & Vicinanza, D. (2016). Large-scale experiments on the behaviour of a generalised Oscillating Water Column under random waves. *Renewable Energy*, *99*, 875-887.

Watson, J. J. W., & Hudson, M. D. (2015). Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. *Landscape and Urban Planning*, *138*, 20–31. https://doi.org/10.1016/j.landurbplan.2015.02.001

Wu, Y., Xu, C., Ke, Y., Chen, K., & Xu, H. (2017). Multi-criteria decision-making on assessment of proposed tidal barrage schemes in terms of environmental impacts. *Marine Pollution Bulletin*, *125*(1), 271–281. https://doi.org/10.1016/j.marpolbul.2017.08.030

# 8 Appendix

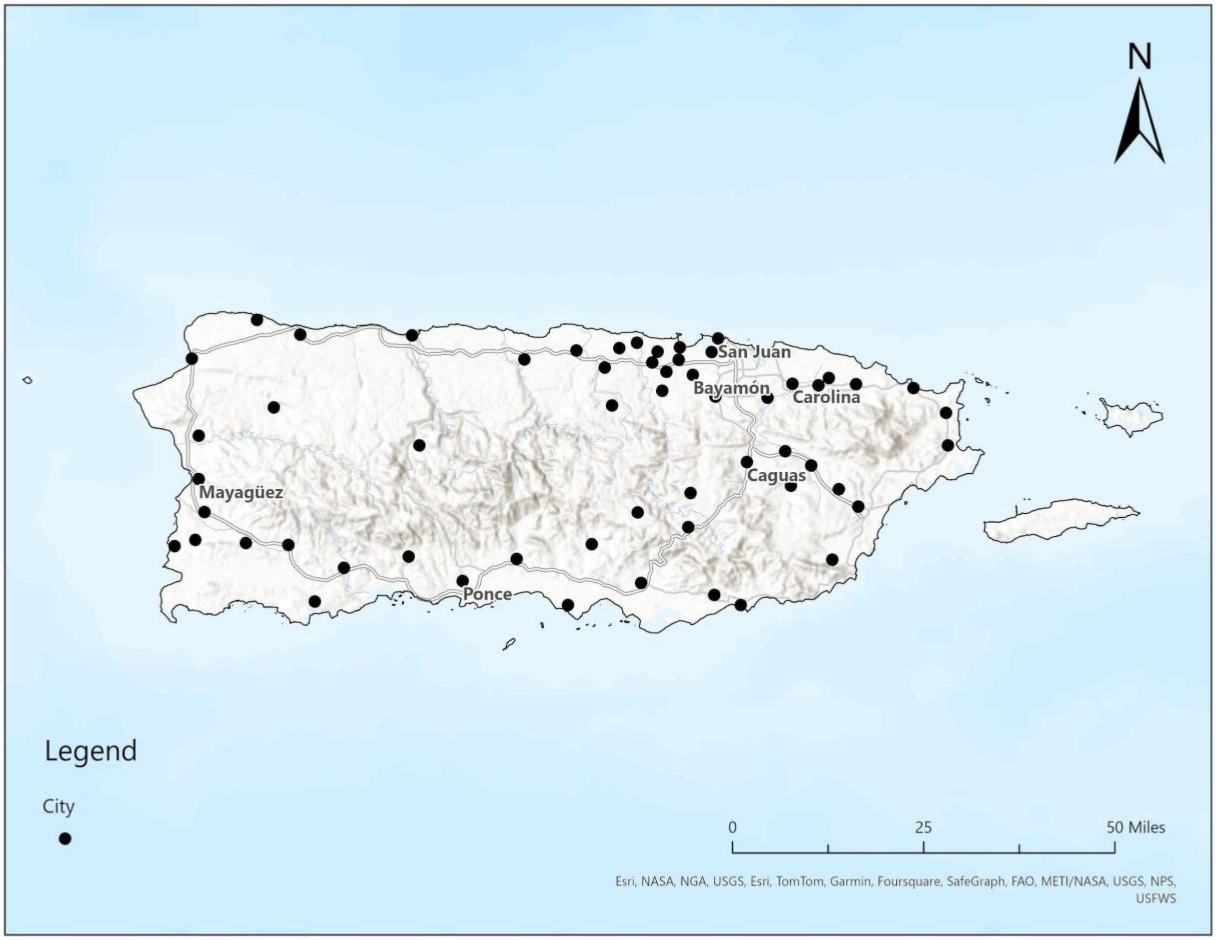


*Figure 8.1 Puerto Rico populated cities*

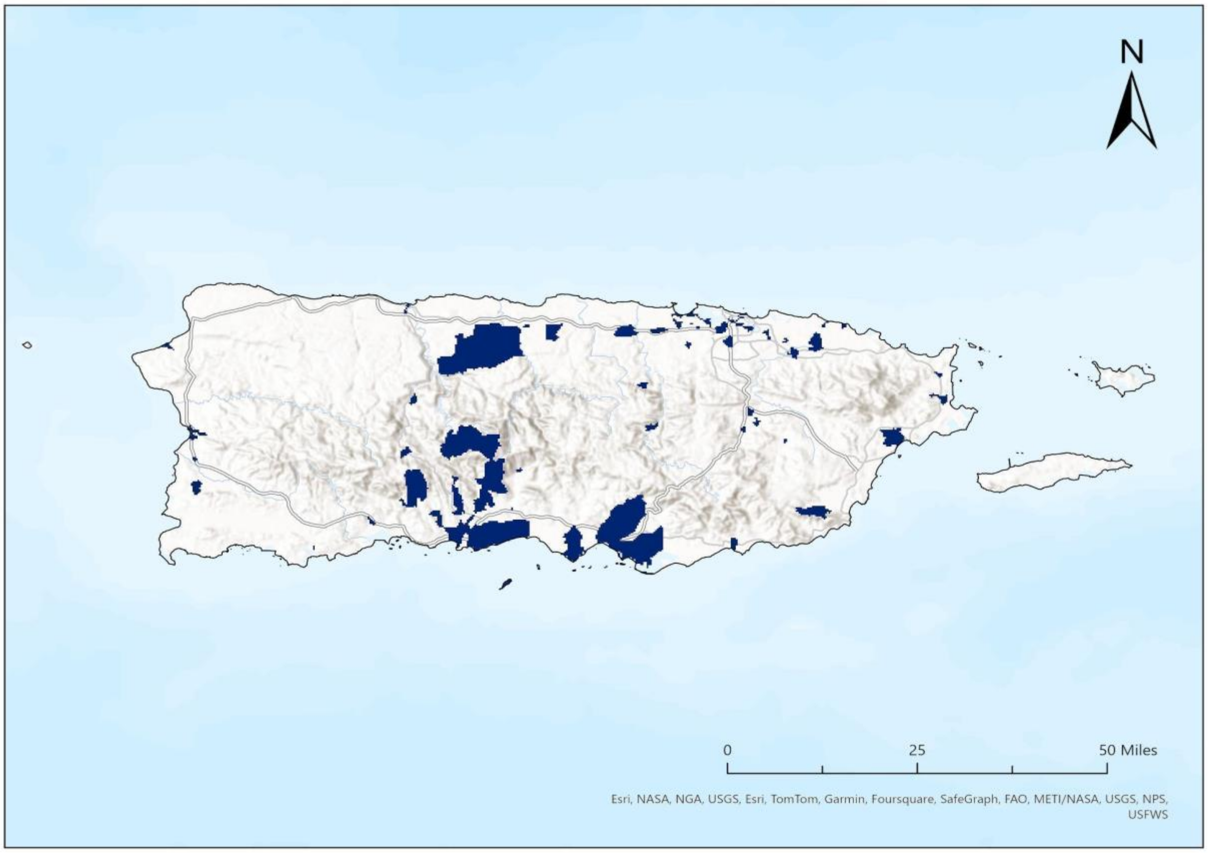


*Figure 8.2 Puerto Rico Justice40 disadvantaged climate change communities*

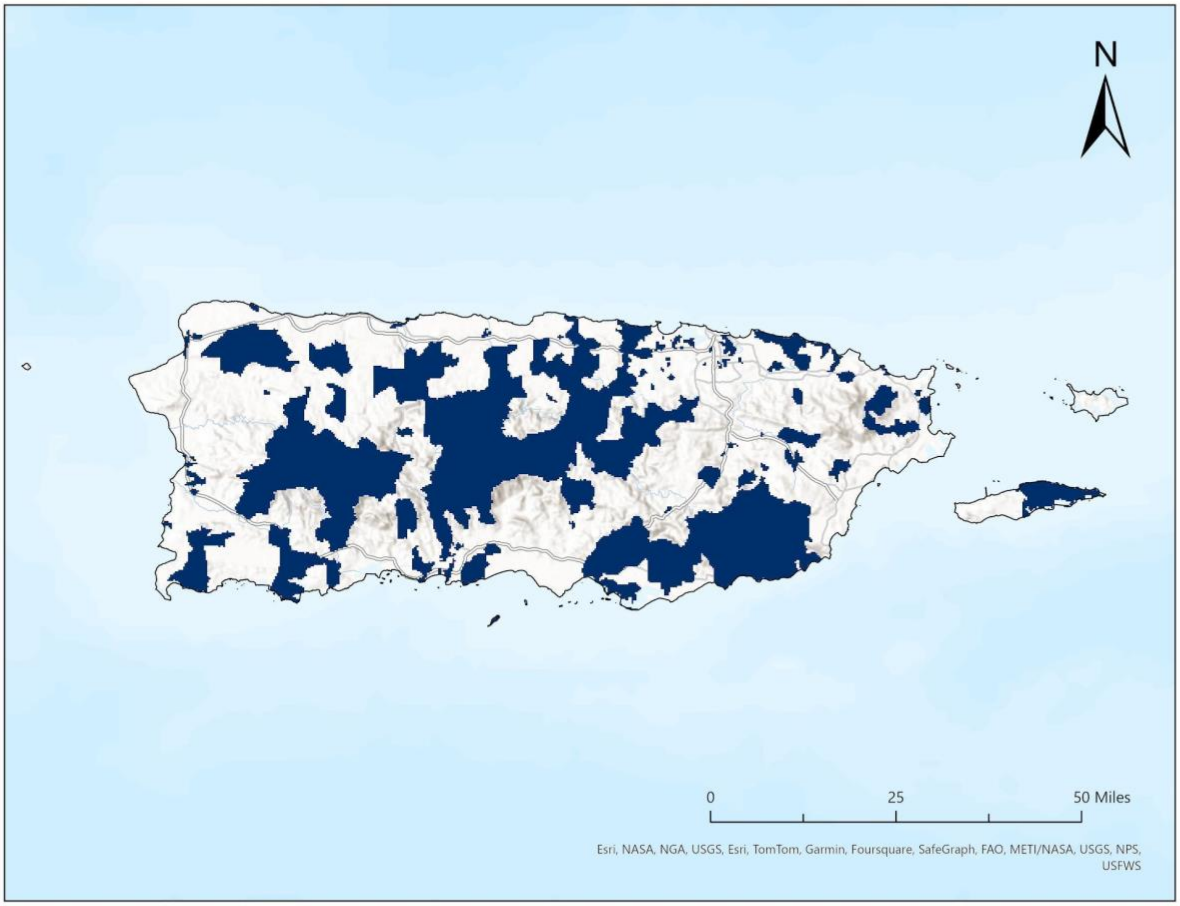


*Figure 8.3 Puerto Rico Justice40 energy disadvantaged communities*

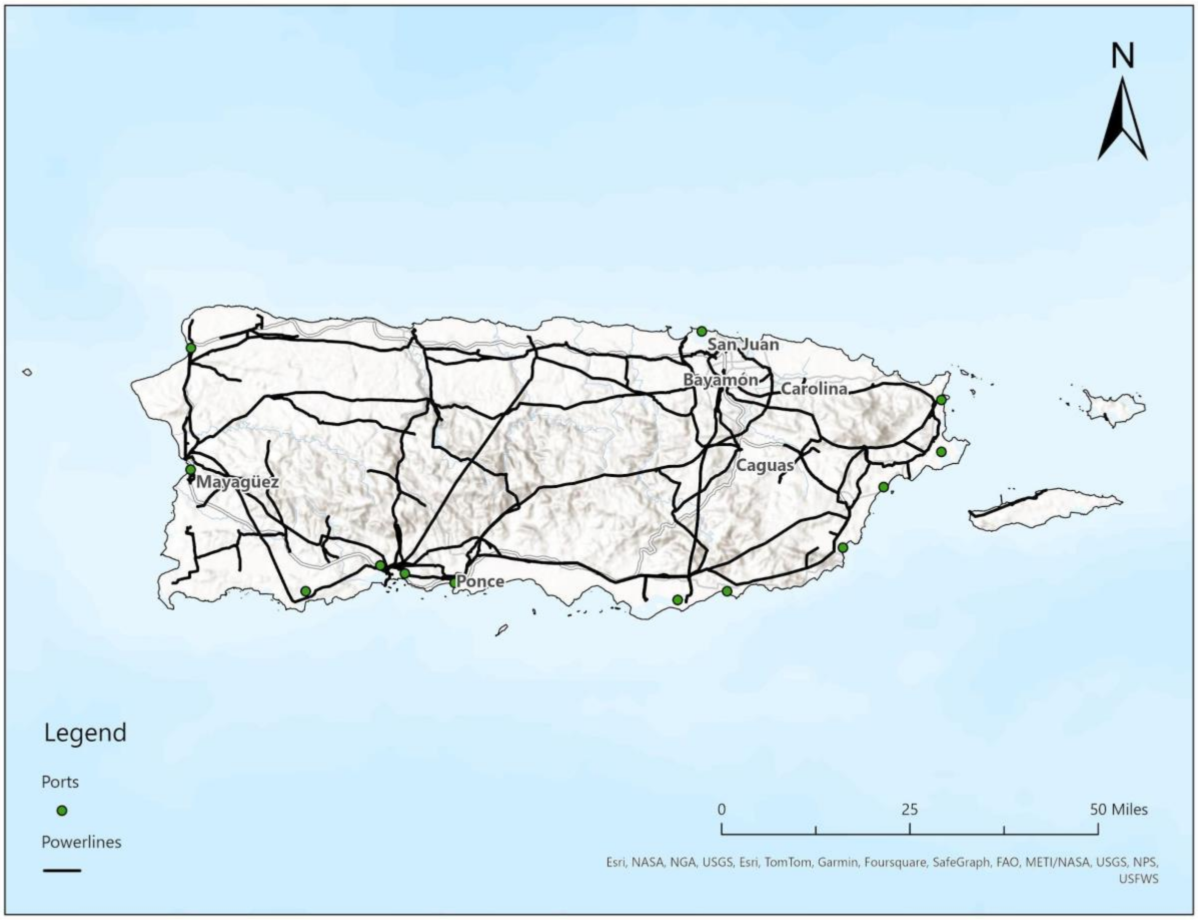


*Figure 8.4 Puerto Rico electric transmission lines and port locations*

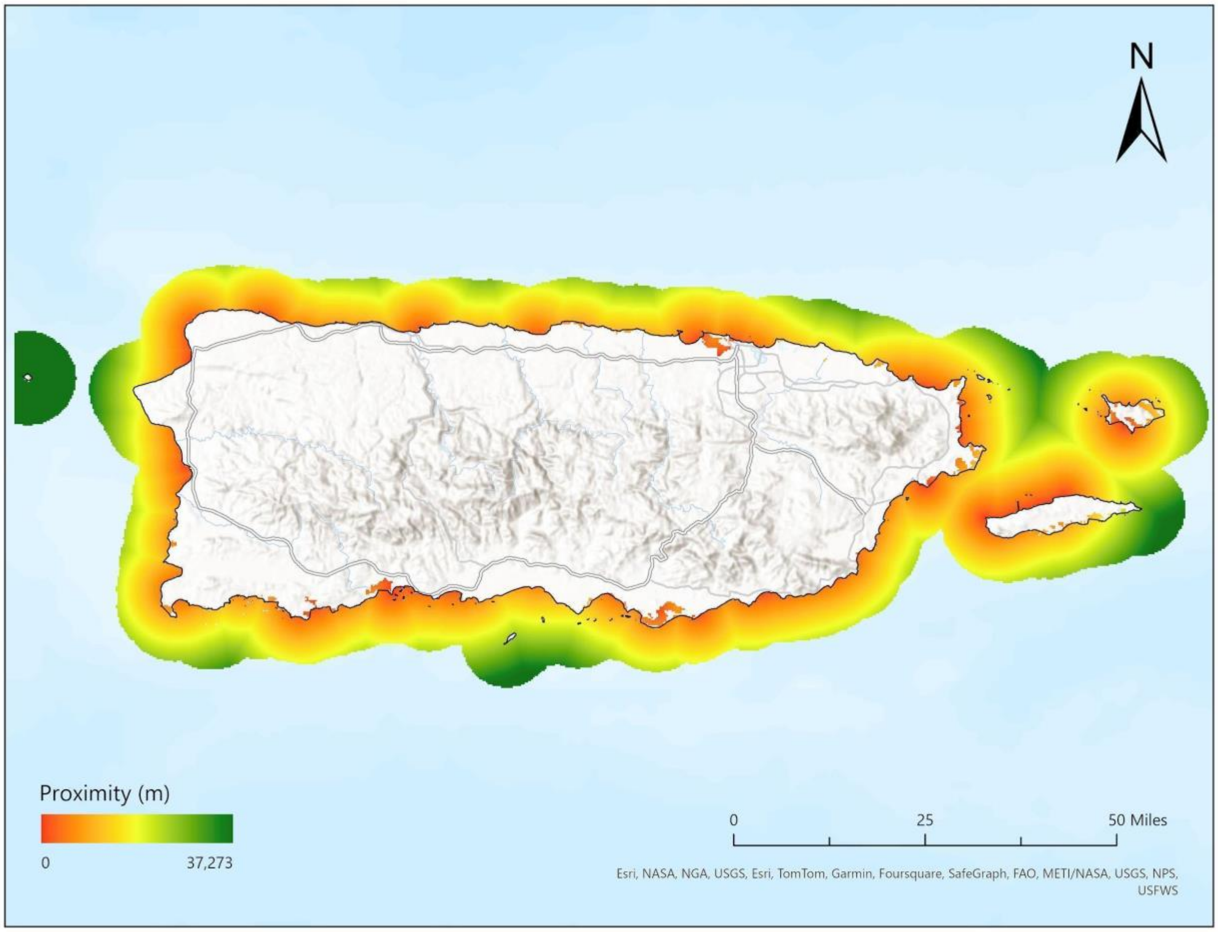


*Figure 8.5 Puerto Rico electric transmission line proximity map. Red represents close distances, while green represents far distances.*

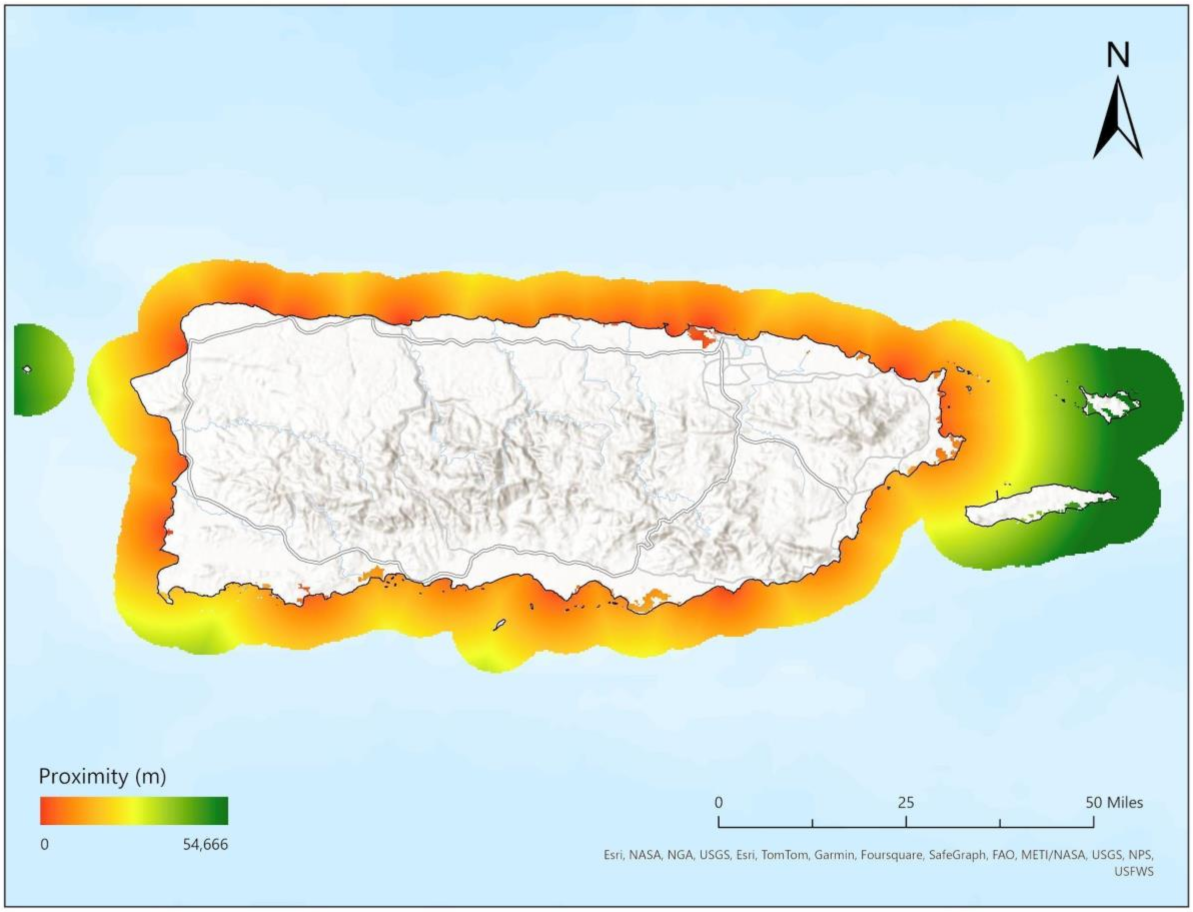


*Figure 8.6 Puerto Rico city proximity. Red represents close distances, while green represents far distances*

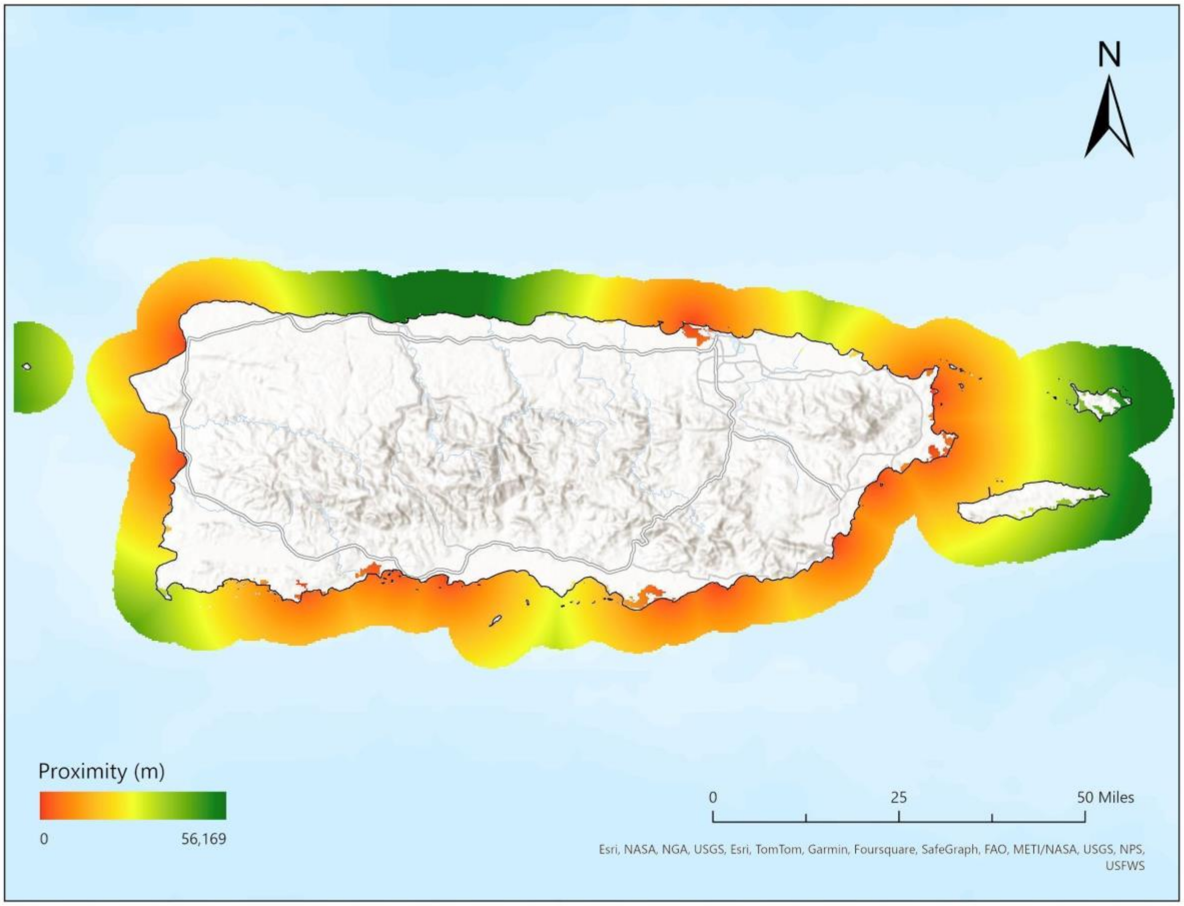


*Figure 8.7 Puerto Rico port proximity. Red represents close distances, while green represents far distances*

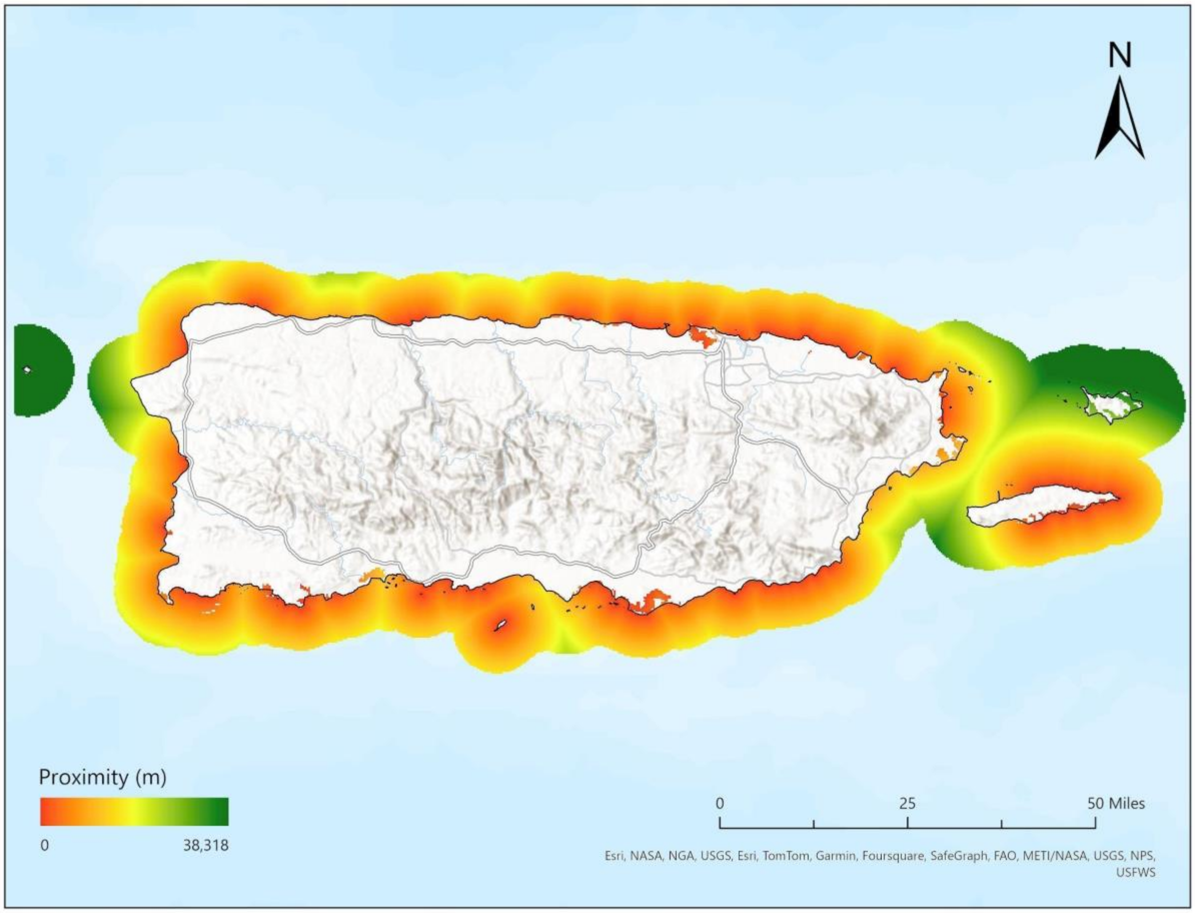


*Figure 8.8 Puerto Rico Justice40 energy disadvantaged communities' proximity map. Red represents close distances, while green represents far distances*

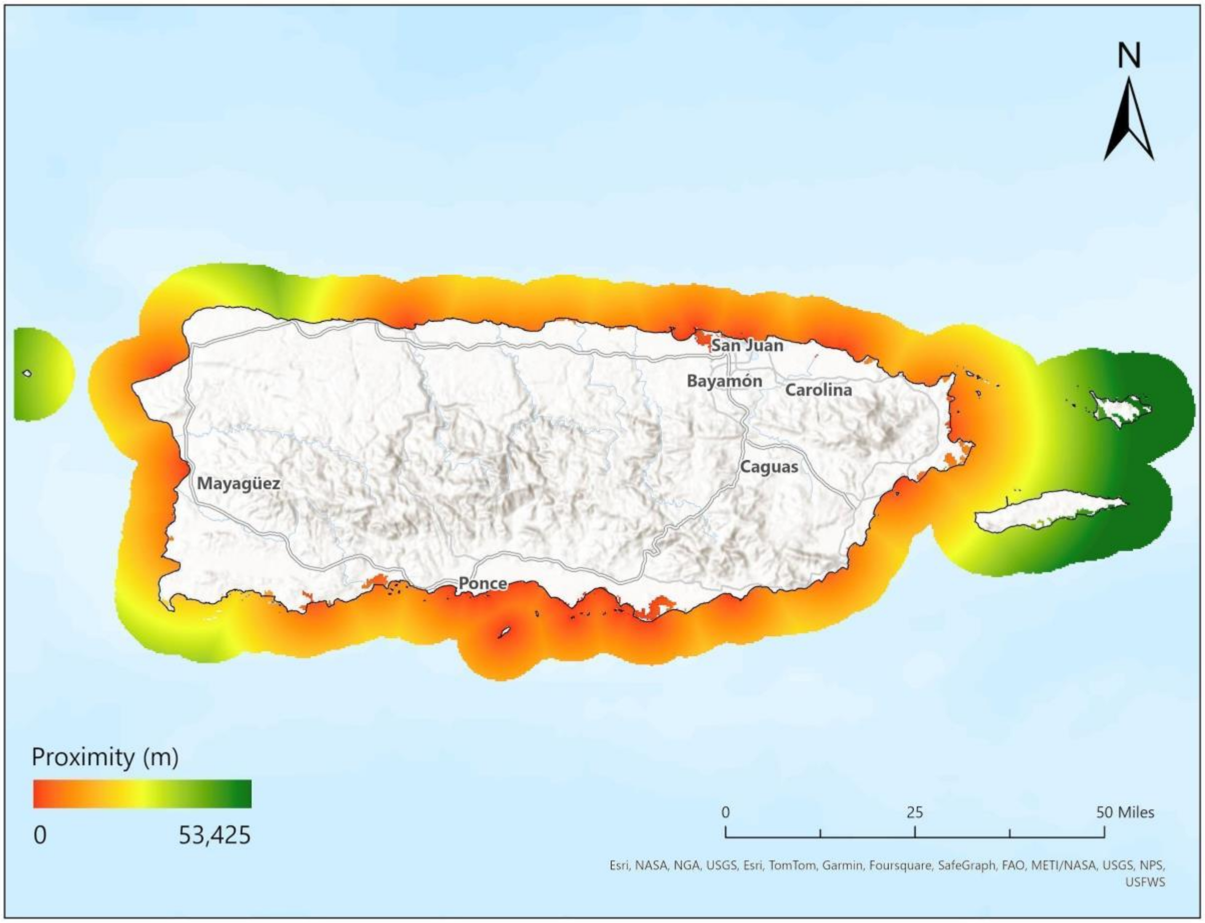
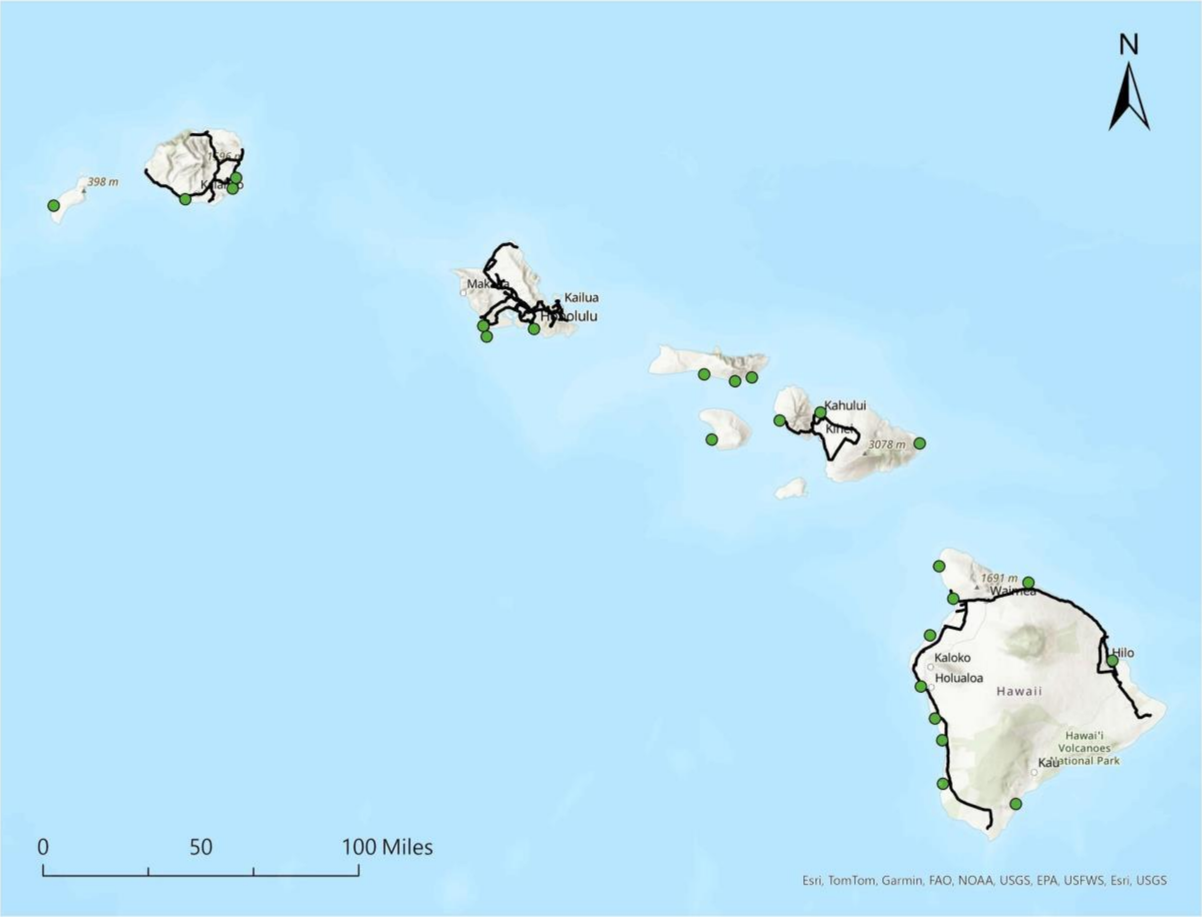


*Figure 8.9 Puerto Rico Justice40 climate change disadvantaged communities' proximity map. Red represents close distances, while green represents far distances*



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS, Esri, USGS

*Figure 8.10 Hawai‘i port and electric transmission line locations*

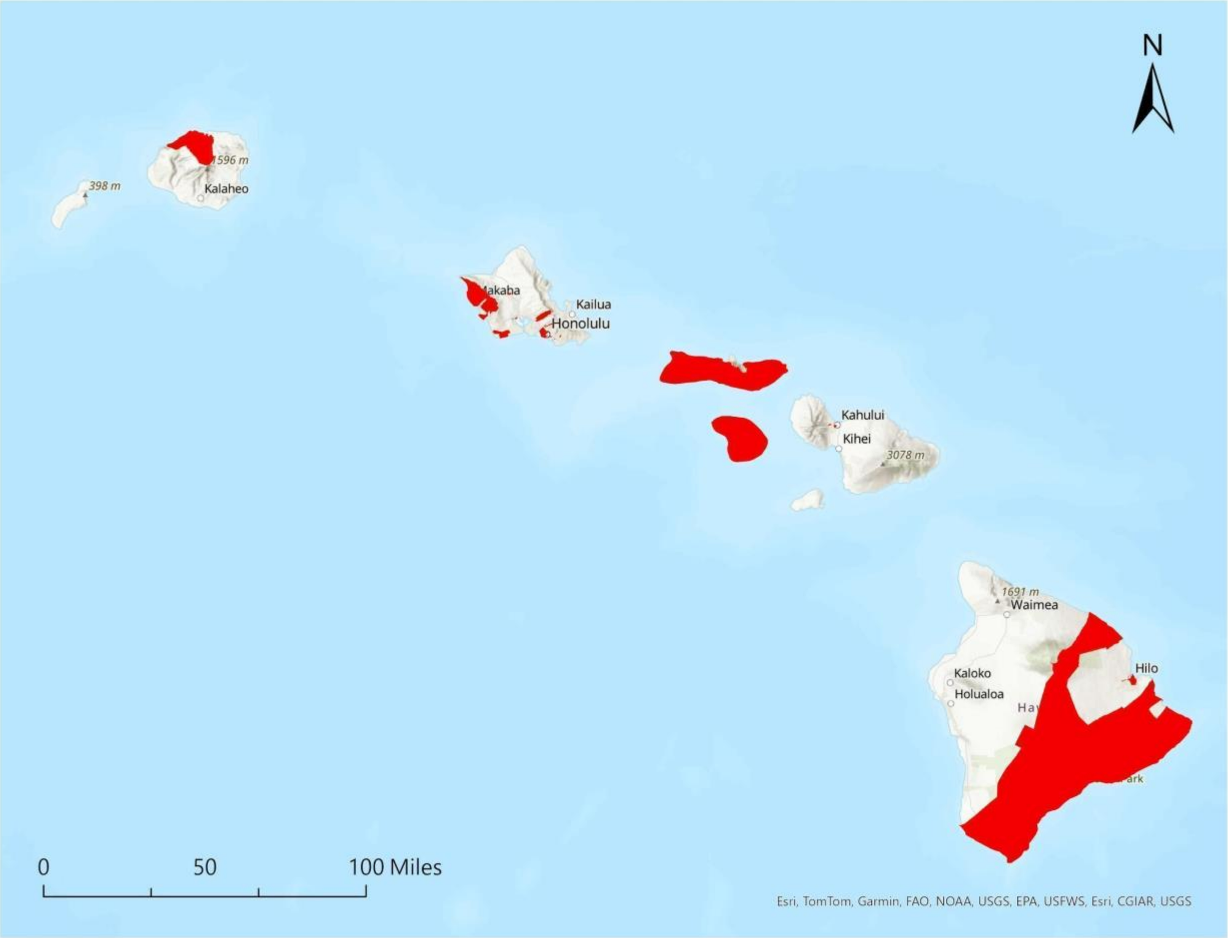


*Figure 8.11 Hawai'i Justice40 disadvantaged communities*

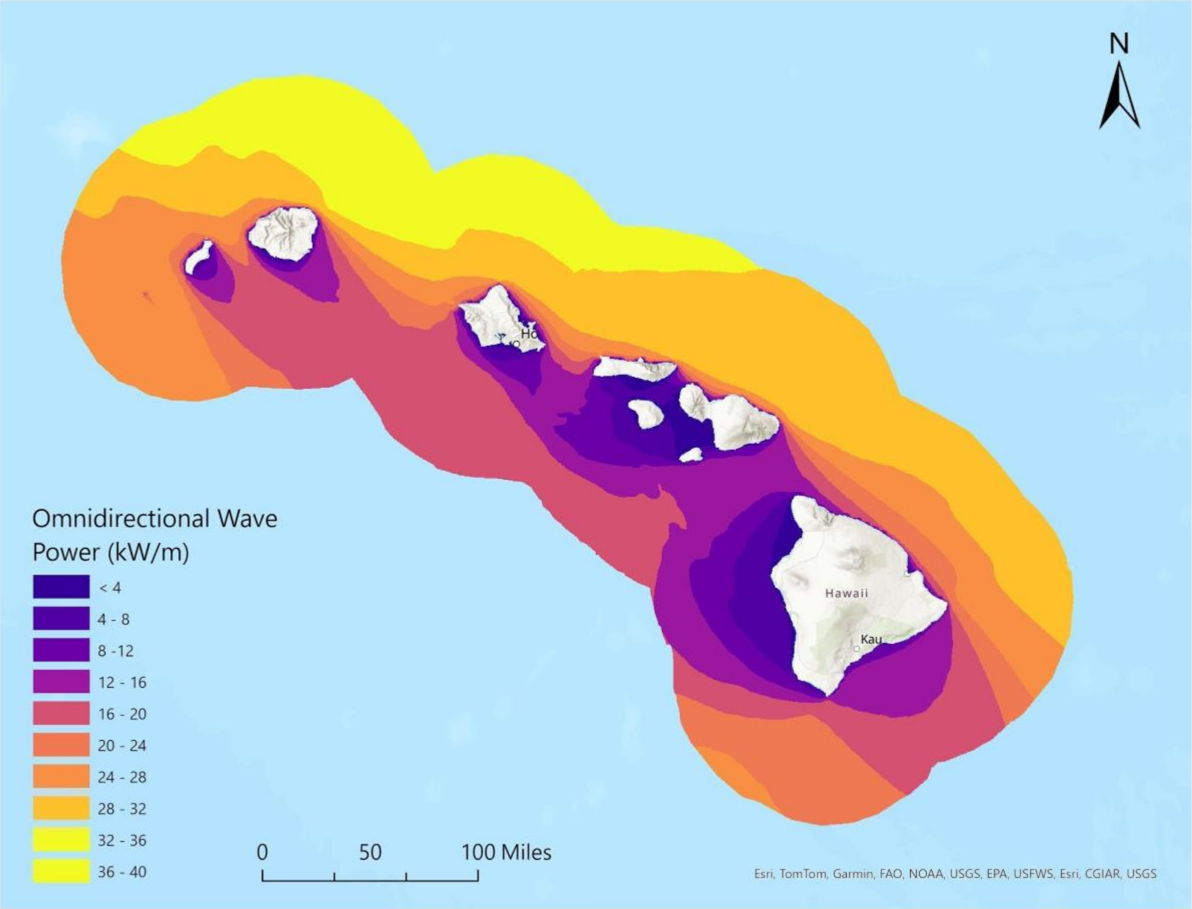
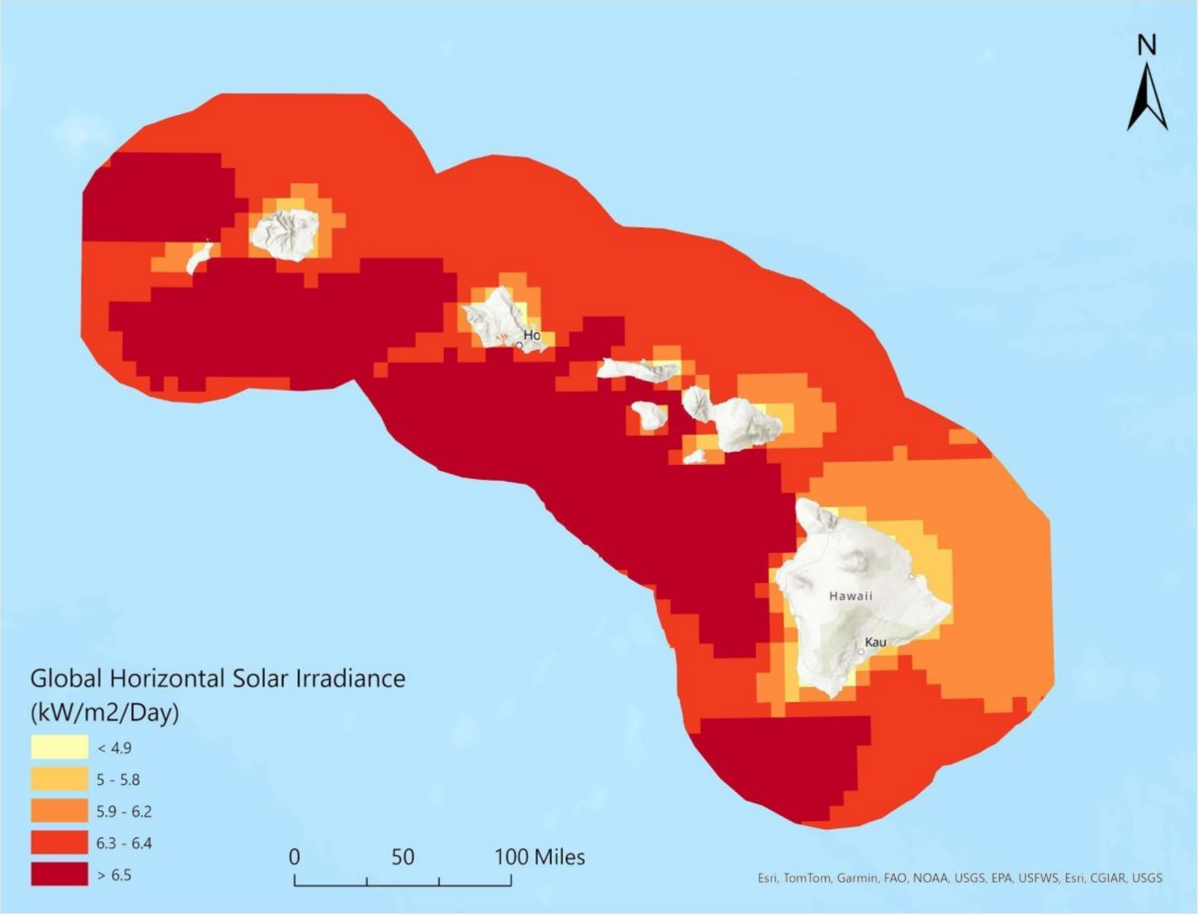
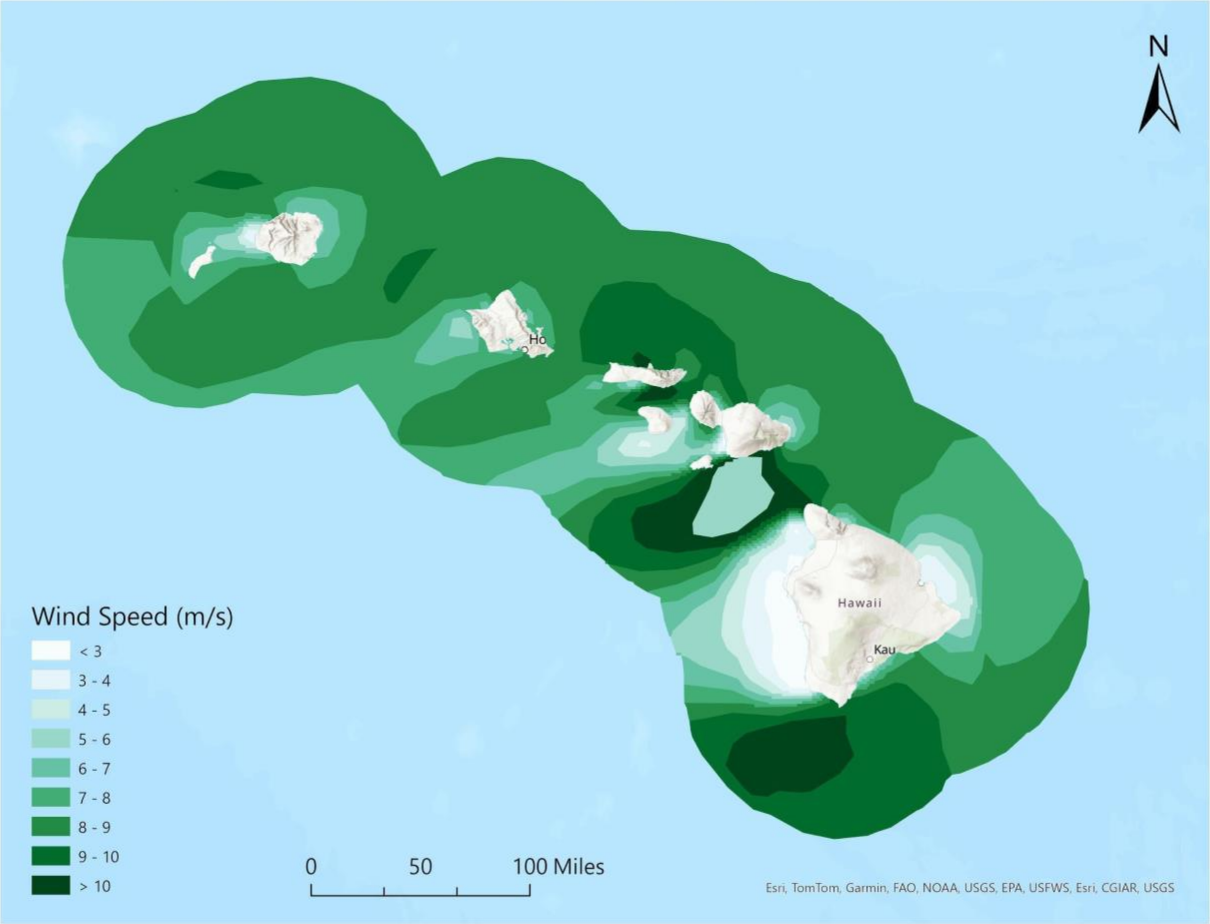


*Figure 8.12 Hawai'i omnidirectional wave power in kW/m.*



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS, Esri, CGIAR, USGS

*Figure 8.13 Hawai'i Global Horizontal Solar Irradiance (GHI) in kW/m²/Day*



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS, Esri, CGIAR, USGS

*Figure 8.14 Hawai'i wind speeds at 100 meters in m/s*

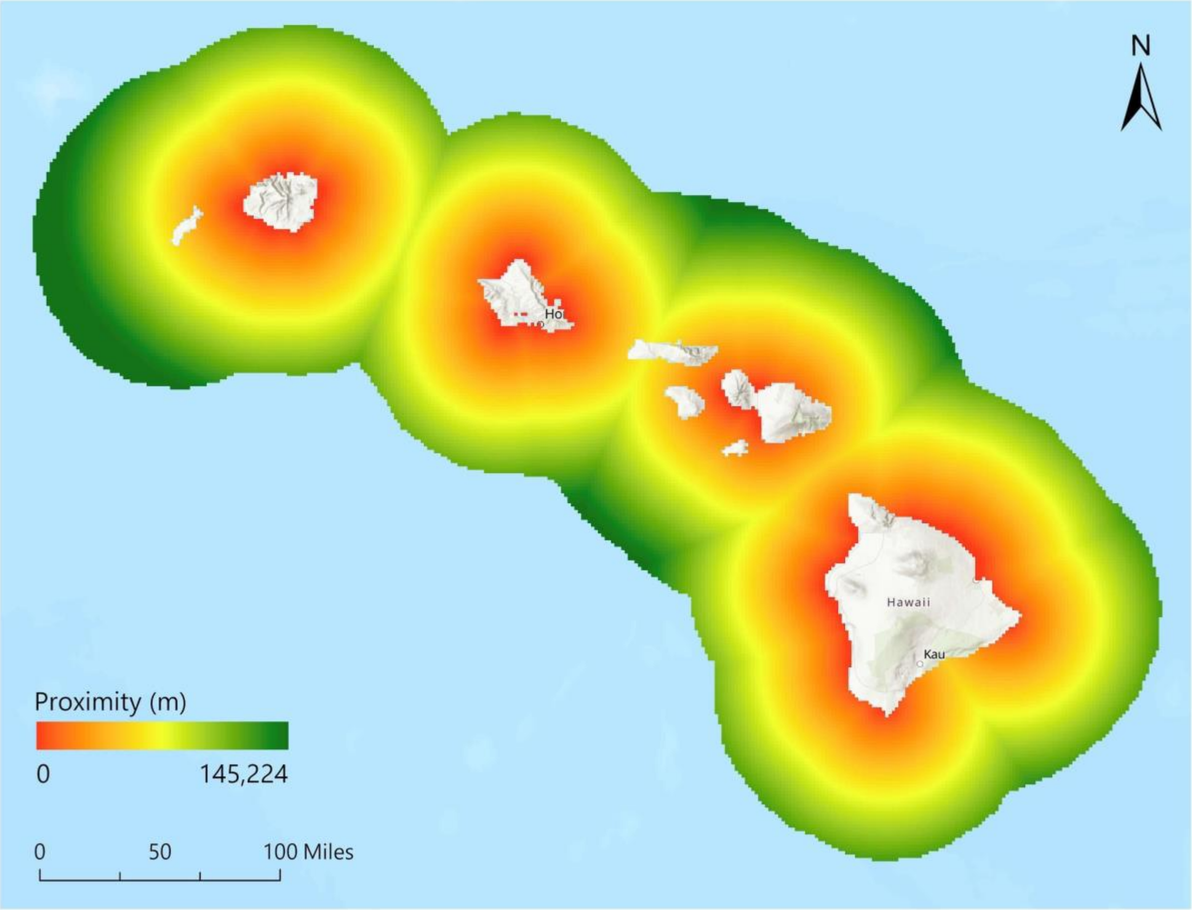


*Figure 8.17 Hawai‘i electric transmission line proximity map. Red represents close distances, while green represents far distances*

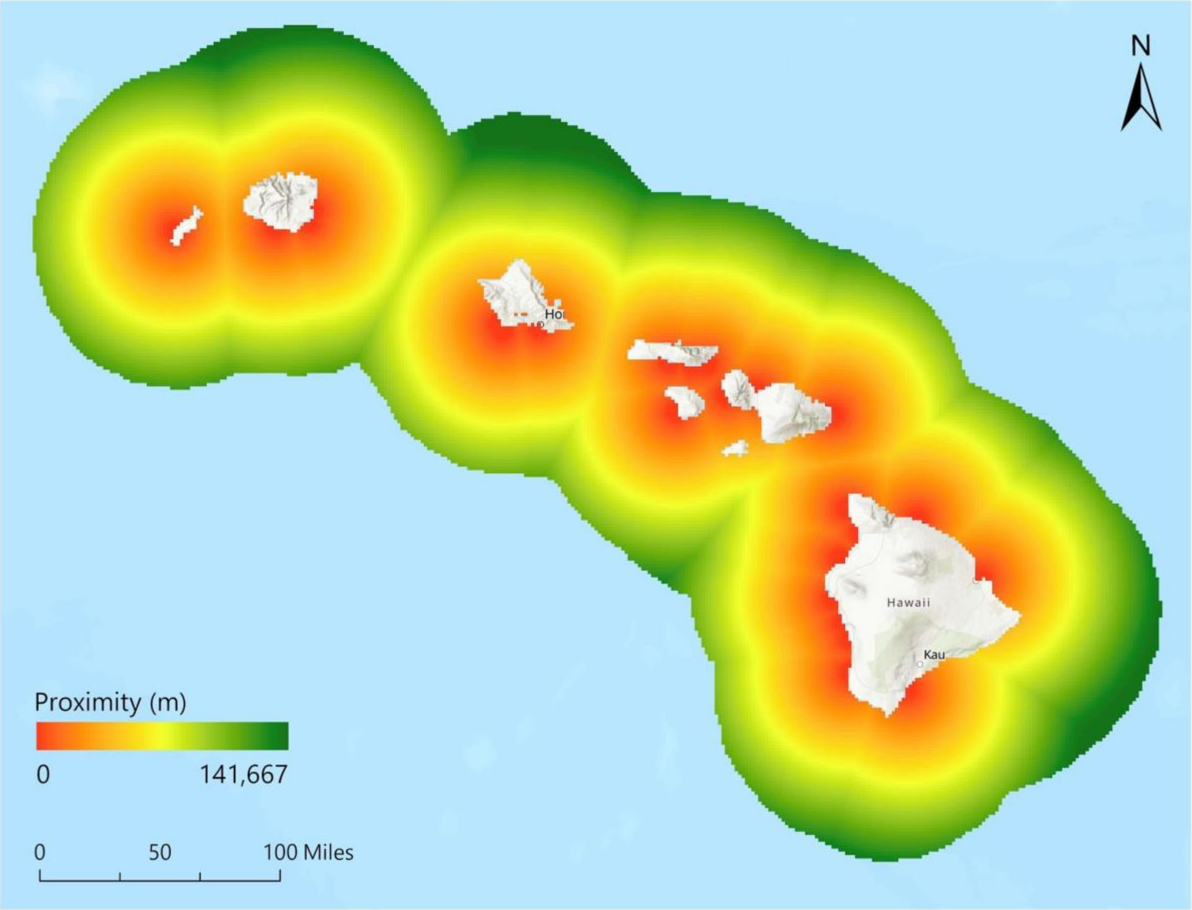


*Figure 8.16 Hawaiʻi port proximity map. Red represents close distances, while green represents far distances*

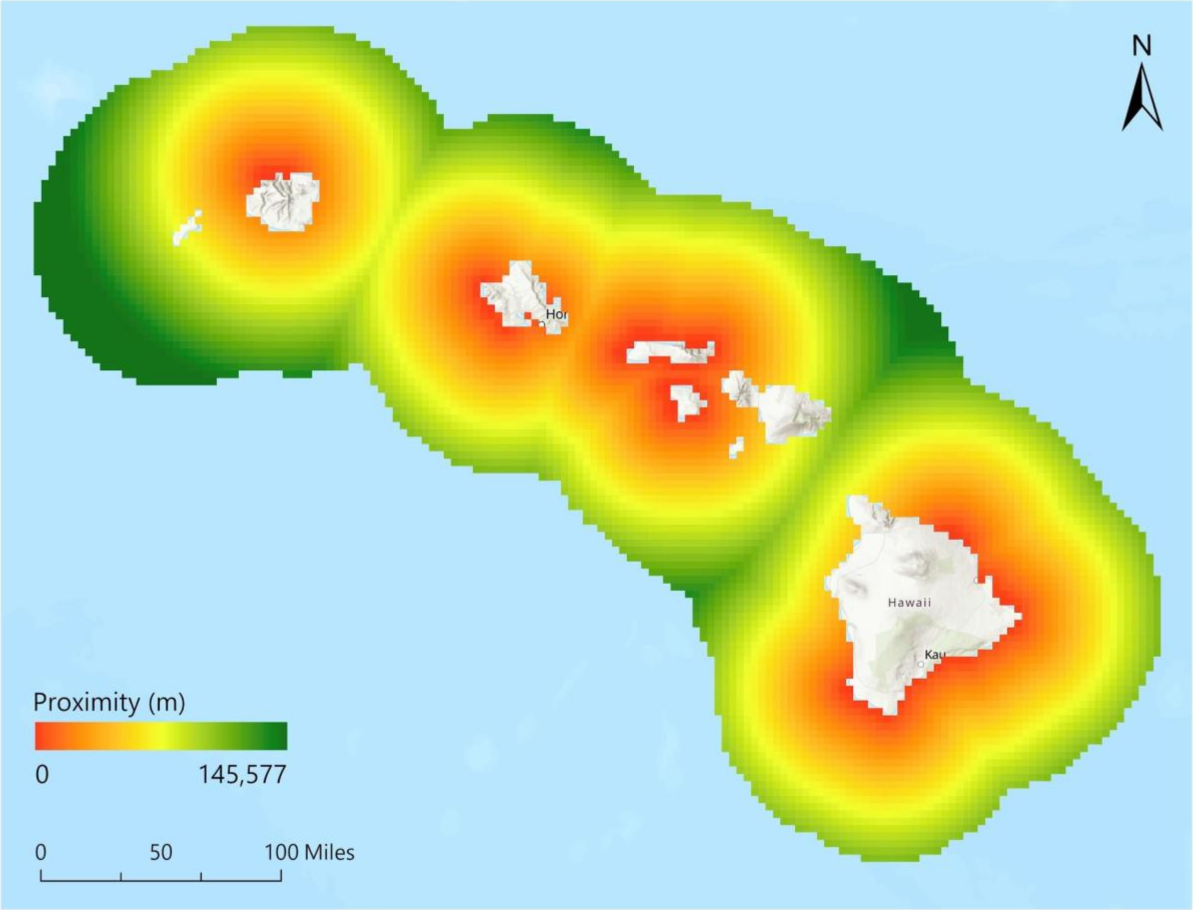


*Figure 8.15 Hawai'i Justice40 disadvantaged communities' proximity map. Red represents close distances, while green represents far distances*

# 9 Glossary

BOEM – Bureau of Ocean Energy Management

CSI-WEC – Coastal Structure Integrated Wave Energy Converter

DOE – Department of Energy

EEZ – Exclusive Economic Zone

GIS – Geographic Information Systems

MCDA – Multi-Criteria Decision Analysis

MRE – Marine Renewable Energy

MPA – Marine Protected Areas

MSP - Marine Spatial Planning or Maritime Spatial Planning

NOAA – National Oceanic and Atmospheric Administration

PV – Photovoltaic

WEC – Wave Energy Converter