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A socio-technical assessment of marine renewable energy potential in coastal communities

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ABSTRACT

Coastal communities face unique socio-ecological risks and vulnerabilities due to their geography and related resource dependencies. The resilience of such communities and their capacity to adapt to social, economic, and environmental change is consequently shaped by the diverse characteristics and values that guide their development. Marine renewable energy (MRE) is one promising solution for augmenting coastal resilience and environmental sustainability while increasing energy security, energy affordability, and socioeconomic benefits. The socio-technical nature of energy transitions more broadly necessitates place-based and multidisciplinary analyses to gain a full picture of the needs of communities. This article uses potential MRE development (specifically tidal energy) in two coastal communities as a lens to explore how social perceptions and MRE's technical potential might be integrated to improve alignment between community values and energy development. We draw on semi-structured interviews with community representatives from Sitka, Alaska and the San Juan Islands in Washington State and present findings on how energy development objectives are shaped by community values, resource relations, and institutional relations. Through modeling exercises, we also show the grid benefits of MRE deployment in the San Juan Islands, highlighting MRE's role in deferring costly electric infrastructure upgrades and reducing fuel imports when paired with solar photovoltaic (PV) or battery storage. These findings offer viable pathways for future MRE research, commercial validation, and deployment that directly respond to the place-based opportunities and challenges of coastal communities.

1. Introduction

Given the pace of global climate change, a rapid transition to renewable energy sources is paramount for societies seeking to avoid its most severe consequences [1]. Due to their geography, coastal communities experience multiple, often compounding social, economic, and environmental challenges that leave them particularly vulnerable to the effects of climate change [2,3]. Renewable energy technologies, such as marine renewable energy (MRE), are an emerging solution for coastal regions that offer decarbonized, sustainable, and scalable opportunities for energy security and resilience [2]. MRE refers to technologies that harness energy potential from the ocean through waves, currents, tides, and salinity or thermal gradients and convert that potential into electricity or other usable forms of energy [2]. MRE technologies are at an earlier stage in development than other renewables but are poised to play a key role in marine sector energy transitions.

A community's capacity to respond and adapt to vulnerabilities posed by climate change through investments in renewable energy depends, in part, on understanding community values and the degree of support for new technologies. Local values and attitudes, histories, geographies, culture, politics, and economic contexts provide the social setting in which communities are embedded. When new development or infrastructure is perceived to threaten those values, communities often engage in place-protective behaviors [4,5], which can include resistance to new forms of energy development. This provides a more complex and nuanced social picture than traditional, often problematic “not in my backyard” (NIMBY) arguments that characterized past explanations for public opposition to renewable energy projects [6].

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Public acceptance and buy-in are necessary for technological and regulatory developments to catalyze investments that support renewable energy transitions, but conflicting values can drive social responses that create unanticipated barriers [7]. Changes to socio-technical systems that characterize energy transitions are dependent on resolving value conflicts between social actors [8]. For example, MRE development can displace commercial fishers, affecting their livelihood and their communities [9]. Space-use conflicts between commercial or recreational ocean users (e.g., aquaculturists, fishers, nature-based tourists) and marine energy developers can affect siting opportunities and catalyze opposition to development, especially when multiple sectors desire exclusive access [7]. Adequate compensation, however, may help galvanize collaboration to mitigate conflict between sectors [10]. Resolving these disputes will require aligning the technical and economic goals of developers and utilities with the values-based development goals of communities and refocusing public engagement around community values and priorities [7].

Siting, developing, and deploying commercial MRE installations are complex processes that depend on specific combinations of resource and technology availability, marine and coastal governance regimes, local environmental conditions, economic factors, and integration of diverse publics in decision-making processes [11]. Moreover, public responses to development proposals can vary based on stage of development and technology maturity, necessitating data that integrate social and technical dimensions and support decision-making [12]. Although research on the interrelated socio-technical challenges of MRE is rapidly growing, DeGroot and Bailey [13] suggest “little is known about the factors informing people's evaluation of MRE developments in their local area, the value systems people employ to evaluate the phenomena that contribute to local livelihoods, or how the character of local areas might be affected by MRE projects” (p. 81). Additionally, there are many uncertainties pertaining to the social, economic, and environmental effects of MRE development on local communities that affect if and where MRE technologies are developed. MRE systems have not been widely deployed, providing researchers an opportunity to focus efforts on understanding the multidimensional interactions of social and technical components, the role of place, and how it might affect public perceptions “upstream” of project proposals [14]. This study employs an exploratory, mixed-method approach to build on recent research and assess the role of socio-technical innovation in MRE development and environmental and economic justice in energy transitions more broadly [15].

Our analysis focuses on two remote coastal communities on the west coast of the United States: Sitka, Alaska and San Juan Islands, Washington. We conceptualize a “community” as a subjective unit of co-constructed identities defined by place-based characteristics, interactions, and values [15,16]. For the purpose of our analysis, we focus specifically on tidal marine energy systems in our two case study locations. We explore the compatibility of MRE technologies within in the context of these two coastal communities and provide a model for future MRE research and development that can reduce community vulnerabilities and improve socioeconomic outcomes amid a changing climate. To that end, the following questions inform the research design:

1. What vulnerabilities to the social, environmental, and economic well-being of coastal communities in the United States can be attributed to energy infrastructure and service deficiencies?
2. How can MRE technologies and related project planning address community vulnerabilities?
3. What contextual characteristics of coastal communities are critical for community-MRE compatibility?

Semi-structured interviews with key community representatives were conducted to understand how community contexts and characteristics may inform renewable energy development as an energy security and resilience solution. Technical analyses and modeling were subsequently conducted to highlight the potential value and role of MRE in addressing community vulnerabilities and reliability needs. Through integration of qualitative and quantitative approaches, we build upon growing mixed-methods literature at the nexus of social sciences and energy research to relate technical advances in MRE to energy resilience for coastal communities and lay the groundwork for future research. In the sections below, we view MRE development through the underlying lens of place-based values to conduct an exploratory socio-technical assessment of the coastal communities of Sitka, Alaska and San Juan Islands, Washington. This assessment highlights how community characteristics inform energy development pathways and vice versa—how energy development can better address community-specific vulnerabilities by identifying community values. Section 2 provides background information on the community vulnerabilities and local place-based values related to social acceptance for MRE development. Descriptions of the coastal communities selected as case studies are offered in Section 3. Section 4 provides the data and methods used in the study. Section 5 provides the study's qualitative findings, and Section 6 covers the quantitative results from the technical analyses. Section 7 offers a discussion synthesizing the results, and Section 8 concludes the paper.

2. Background: community vulnerabilities, values, and marine renewable energy

Approximately 10 % of the global population lives in coastal areas (or land that is below 10-meter elevation) [3], and more than 50 % (~4 billion people) lives within 200 km of a coastline [2]. Coastal and island communities refer to people living at the interface between the land and the sea, where ecosystems and human activities are especially interconnected [4]. Although coastal communities are typically defined through semi-arbitrary geographic, environmental, or political boundaries (e.g., inland distance from high tide) and broad socioeconomic characteristics (e.g., marine resource dependency), these communities are too diverse and dynamic to easily define [5]. Exogenous forces (such as population growth, urbanization, and globalization) and endogenous forces (such as local tourism and related economic activity) can exacerbate changes to community composition and structure [5].

Coastal community vulnerabilities create basic unmet needs, as well as complex and nuanced resource dependencies that affect the social, ecological, and economic well-being of the community. Values reflect the sociocultural and environmental contexts in which people and communities are embedded, leading to a diverse array of perspectives, beliefs, and ideologies that structure community identity, which presents challenges to achieving consensus at the community level on how to best address complex social and environmental problems [17]. A high-level overview of pertinent literature was conducted to characterize the vulnerabilities faced by coastal communities and the socio-technical linkages between community values, social acceptance of new technologies, and potential deployment of marine renewable energy systems. A comprehensive and exhaustive review of the literature is beyond the scope of our analysis. The exploratory nature of our study, however, necessitates grounding our discussion in an understanding of coastal community vulnerabilities, values, social acceptance, and MRE technologies. Section 2.1 discusses community vulnerabilities, which are grouped into four key dimensions—economic, social, technical, and environmental—which are discussed below. Community values are discussed in the context of social acceptance of renewable energy technologies more broadly. Finally, we review the state of MRE technology and its potential to address coastal vulnerabilities identified in our background review.

2.1. Coastal community vulnerabilities

2.1.1. Economic vulnerabilities

Coastal community economics are often intertwined with geographic and social factors—like relative isolation and limited population—that drive the use of natural resources as the predominant means of production. Dependence on natural resources, not only for subsistence needs, but also for livelihood activities, is especially prevalent in coastal communities. Industries dependent on natural resources and the ecosystem services provided by the environment, such as tourism, fishing, forestry, mining, and aquaculture, are among the major economic sectors in coastal communities [2]. Overdependence on one or two industries in these communities can introduce long-term vulnerability and economic instability and result in underdevelopment within other economic sectors [18]. For example, long-term overdependence on tourism can create economic vulnerabilities through seasonal unemployment [19,20], waste hazards associated with cruise ships and charter boats [21], ecologically destructive tourist activity [22,23], and fluctuating value of commercial, investment, and second home properties with tourist demand for their use [24]. Beyond tourism, community dependencies on other industries, such as fishing and aquaculture, also pose unique vulnerabilities (e.g., species depletion, habitat destruction) [2]. By providing water and space for shipping and ports, as well as salt and sand for use in infrastructure and other purposes, coastal communities also export or provide their limited resources for distant economic needs.

Ultimately, the embedded nature of ecosystem goods and services in the economic profile of these communities results in vulnerabilities associated with dependence, including industry seasonality, boom-and bust-cycles tied to infrastructure construction and new housing developments, and cascading economic dependencies (e.g., tourism and amenity migration) [25,26]. Aside from these community-scale, "micro" vulnerabilities, coastal communities are also susceptible to "macro" scale vulnerabilities, or those related to national level socioeconomic changes. These can include economic shocks from changes in trade policy, exchange rate fluctuations, sociopolitical events, shifts in commodity prices, as well as climate change effects on resource availability (i.e., quality and quantity) and local industry viability [26,27].

2.1.2. *Sociopolitical vulnerabilities*

Social characteristics can influence the extent of resource dependency, and therefore economic vulnerabilities, in a community [28,29]. Social factors influencing the economic dependency of a particular coastal community can include governance structures, which dictate access to land, resources, and means of production; educational attainment levels that influence skill development and related job opportunities; and characteristics of community cohesion, such as gender equity, agency, and transparency in decision-making [30]. The economic longevity and sustainability of resource-based industries is further shaped by political actions, such as environmental regulations and laws that promote the conservation and management of resource stocks (e.g., fisheries) [31].

The amount of government aid and intervention plays a role in diversifying modes of economy or the presence of multi-generational poverty, which in turn limits the availability of work opportunities to residents (usually marine resource dependent work) or prevents them from leaving to develop skills outside traditional employment pathways. The number of subsidies and funding opportunities available to communities can influence the level of work diversification, with more diversification resulting in less susceptibility to resource changes. However, insulation from such variability via economic aid is often difficult to acquire. Social and institutional structures can also compound vulnerabilities associated with resource dependency. For example, lack of access to land tenure or ownership limits accessibility to other types of work; inadequate education can leave resource users with few useful skills outside their traditional activity; and unequal distribution of social capital within a community may mean there are limited networks for individuals to expand access to other resources or to decrease dependency on one resource [30].

2.1.3. *Technical vulnerabilities*

High energy costs and energy infrastructure problems are common burdens for many coastal and island communities [32]. High dependency on imported fossil fuels can also introduce difficulties in terms of energy supply and energy security, especially considering climate change effects [33]. For example, many isolated island resort communities of Alaska have diesel-generated microgrids that depend on a few bulk fuel deliveries each year, which are susceptible to supply chain disruptions and fuel price volatility. In these communities, the energy cost is higher than the national average—sometimes more than $1/kWh (compared to an average of nearly $0.14/kWh in 2021 [34]—and varies significantly with the price of oil) [35]. Further, lack of access to financing and affordable manufacturing makes it more difficult to implement sustainable solutions in local communities [36].

Another issue within these communities is aging grid infrastructure, which exacerbates power quality issues and outages. Climate change effects have only catalyzed the age and inability of existing infrastructure to provide power for lighting, water pumping, and critical services. For example, in Maine, where coastal electrical infrastructure in some parts of the state is more than 50 years old, recent extreme weather events have caused residents to experience a 50 % increase in outage duration over the past two decades [37].

2.1.4. *Environmental vulnerabilities*

Geographic isolation plays a large role in natural resource dependency as it can make a community reliant on one industry due to area, resource, or population limitations. The geographic isolation and remoteness of these communities, combined with limited energy resources for self-sufficiency and few financing pathways for development, can force communities to rely on expensive imported fuels and/or lead to underinvestment in sufficient grid infrastructure and energy services [33]. Resource dependency in coastal and island communities is also increasingly shaped by climate change effects, which can disrupt traditional livelihoods and resource-dependent value streams to communities vis-à-vis degraded resource quality and lower or more unpredictable availability of resources. For example, increased sea-surface temperatures in the Florida Keys have pushed marine life to their upper thermal temperature limits, driving coral bleaching events, massive die offs of sponges and seagrasses, proliferation of invasive species, and toxic cyanobacteria blooms [38].

Coastal communities are also subject to environmental vulnerabilities in the form of natural hazards. The size and effect potential of common natural hazards—including hurricanes, tsunamis, coastal storms, landslides, coastal erosion, and sea level rise [31]—are dependent on ocean conditions that are becoming increasingly unfavorable with climate change [39]. As climate change worsens the frequency and severity of these natural disasters [40], the costs paid in lives, property, and economic damage increases. For example, the 2020 Hurricane Laura that breached southwest Louisiana—the strongest to ever hit the state—caused at least 47 deaths and $19 billion in damages [41,42]. Climate change not only exacerbates environmental vulnerabilities but also the economic effects of those vulnerabilities, making societal decisions related to resilience all the more difficult [6,13,14,17,43–58].

2.2. *Marine renewable energy and socio-technical innovation*

Values reflect individual and collective priorities, or "criteria through which people select and justify actions and evaluate people and events" [54] and serve as a psychological lens for translating broader principles (e.g., sustainability, security, independence, etc.) into specific attitudes and behaviors [43,55]. Other factors shown to affect social acceptance (or opposition) to siting various energy projects include: attitudes and norms [13,51], socio-economic factors [58], place attachment [47], trust and confidence in governmental institutions [45,50], perceived risks and benefits of new technology [45], locally derived benefits and ownership structures [56] environmental and/or ecological impacts [52], and transparent and just engagement practices [46,48,49]. Understanding how these factors are linked to social acceptance of new technologies can help developers, planners, regulators, and utilities anticipate barriers to their development, ensure equitable distribution of the benefits from technology deployment, and adequately engage the public in addressing the unique vulnerabilities that coastal communities face.

All this to say, community values inform community responses to vulnerabilities. For some communities, MRE technologies have already been identified as a response to climate-resilient energy needs [59]. DeGroot and Bailey [13] found in an evaluation of community perceptions of MRE in the United Kingdom that "local economic and social multipliers" created "potential for MRE to contribute toward maintaining the long-term viability of island communities by helping to address their economic and social vulnerabilities" (p. 92). MRE potential in the United States is geographically diverse: wave and ocean current energy resources are abundant in the Pacific Ocean and Southern Atlantic Ocean, respectively, while substantial tidal energy can be found in both. When used to capture these local resources, MRE technologies can help reduce vulnerabilities associated with energy prices and energy dependence on mainland jurisdictions, as well as flood potential when integrated in storm surge barrier designs [3,60]. Additionally, MRE systems can be developed over time, meaning that small communities can start with a single unit and expand thereafter. Multiple MRE technologies can capture energy from different resources, although each are in varying stages of research and development and no MRE technology has achieved commercial deployment to date [61]. With low deployment levels, there is still uncertainty over the technical capabilities of MRE, long-term reliability, and environmental effects [62] and the costs per kilowatt of MRE technologies remain much higher than their more developed wind and solar counterparts (cost estimates vary widely across the literature) [63]. However, MRE still offers the potential to support decarbonized, community-based, low-cost, and scalable opportunities for energy security and resilience for coastal communities.

As MRE technology improves, research and preliminary deployments have shown multiple ways that communities can use MRE power to address local vulnerabilities. Research by the U.S. Department of Energy [35] highlights how MRE technology can be co-located with marine infrastructure to expand local maritime industry, such as aquaculture, or help communities tap into new marine economy sectors [64]. Likewise, MRE can be used to power conservation initiatives, such as cleaning up oil spills or coral restoration, while reducing carbon emissions [35]. Additionally, MRE technologies could also have positive social effects by helping communities use local resources to promote energy independence and resilience. Preliminary projects have shown that MRE infrastructure could be adapted to address energy and water scarcity simultaneously in response to climate change. The Carnegie Perth Wave Energy Project in Australia [57] and the U.S. Navy-owned ocean thermal energy conversion (OTEC) plant on the Kona Coast of Hawaii [65] are paving the way for coastal and island communities across the world to expand desalination infrastructure using decarbonized energy while conserving water. Table 1 below offers a summary of MRE technologies, their commercialization status, and technical potential; maps community vulnerabilities to benefits offered by MRE technology; and demonstrates how these devices could offer potential solutions.

3. Case study contexts

U.S. coastal regions, such as southeast Alaska, face hazards related to the remote and isolated nature of their geography, which may limit the community's access to energy, water, and food resources [74]. Many remote coastal and island communities, such as the San Juan Islands in Washington State, must import fossil fuels (e.g., diesel) over long distances, which can drastically increase costs and uncertainties over the timing of access [75]. High energy costs and aging energy infrastructure, the latter of which exacerbate power quality issues and outages, can deepen existing vulnerabilities in these communities. With a variety of technical vulnerabilities related to energy affordability, quality, and reliability, many coastal communities are in a prime position to leverage a resource abundantly available to them—water—in order to produce local, cost-effective power. Specially-engineered generators can be deployed along coastlines to harness the substantial energy generated by ocean movements, including tidal currents, which are among the most reliable marine energy sources for electricity generation [76]. Compared to other types of MRE (e.g., wave, salinity gradient), the rise and fall of tides is a more predictable and continuous phenomenon—lending to greater reliability when converted to power—but locations with sufficient energy for harvesting are limited (due to the large difference in tidal range required) [77]. The San Juan Islands, Washington, and Sitka, Alaska, are two locations in the United States in which preliminary feasibility analyses have identified strong tidal flows for electricity generation [78–80]. In fact, a demonstration tidal energy pilot project is underway at the former location, where proximity to utility infrastructure and optimized siting conditions (with minimal environmental effect) allow for the deployment of multiple tidal stream generators capable of powering up to 400 homes in the area [81].

Sitka (Alaska) and San Juan Islands (Washington) were selected as case study communities for our analysis based on their tidal resource quality and locational suitability for tidal generator deployment, local interest in exploring MRE feasibility, and experiences with strategic energy planning to address various socioeconomic, technical, and environmental community vulnerabilities. Community-based organizations in both locations (i.e., the Sitka Conservation Society and Islands Climate Resilience group of San Juan Islands) have produced forward-looking reports on energy management strategies that encourage energy and cost savings and reduce the local carbon footprint [82,83]. Partnerships have also informed various planning efforts and potential renewable energy projects in both communities, with collaboration from national agencies and laboratories in the case of Sitka [84,85], and the local electric provider in the case of the San Juan Islands [86]. This section provides a brief description of each community to provide broader background and set a high-level case study context.

3.1.1. *Sitka, Alaska*

The city of Sitka is located on parts of Baranof Island and Japonski Island in the Alexander Archipelago on the outer coast of Alaska's Inside Passage. Despite being only accessible by water or air, Sitka ranks as Alaska's fourth largest city with just under 9000 people [87]. While the city's poverty rate (6.6 %) is well below the national average (11.4 % in 2020), economic disparities are large: for Sitka tribal members—who make up nearly half the community—the unemployment rate is over twice the city average at 17 % [88]. These demographics are of particular relevance because broader community vulnerabilities may not be experienced equally; that is, the level of exposure to and impact of economic vulnerabilities within a community will be heightened for those members that are most economically disadvantaged. In terms of economic activity, the region has large oil, mining, and fishing industries [89] and is known for its history of gold mining and fish canning [90]. Sitka's natural environment is very important to both the history and cultural context of the region. Climate change has already disrupted local salmon populations and reduced Yellow Cedars, both of which have ties to Native Alaskan culture and subsistence fishing [91]. While Sitka predominantly relies on hydroelectric power, diesel generators are used for backup power [82], heightening the pollution threat to the community's economy, environment, and indigenous culture. A 2012 report by the Sitka Conservation Society states that the greatest energy issue facing Sitka is the rising cost of environmentally-taxing oil-based fuels, used mainly for heating and transport in the region [92]. An uptick in the use of supplemental diesel generators—at significant cost to the utility—has been a result of more and more households converting to electric resistance space heating (due to more favorable electric rates).

Table 1
Marine renewable energy technologies and community energy benefits.

Tech	Description	Commercial status	Technical potential	Community benefit examples
Wave	Wave energy converters capture the interaction dynamics of wind on the surface of the ocean in order to generate power. Wave resource potential is high between 30° and 60° latitude on the West Coast of the United States, capable of providing baseload, reliable power.	Limited sustained deployment in the pre-commercial stage.	The most abundant MRE resource in the United States with a total technical resource estimate of 1400 TWh/yr [66].	In Chile, the Marine Energy Research and Innovation Center is developing a project to co-locate aquaculture and wave energy converters [53] which could help grow the coastal aquaculture economy.
Current	Current power generating turbines capture the energy generated through tidal, river, or ocean current resources. There is high potential in straits and inlets where water moves faster [67]. This can aid in freshwater production [68].	While the devices are still in the pre-commercial prototype stage, current resources are more predictable than wave energy, making it easier for technologies to reach commercialization.	The technical resource estimates in the United States for tidal are 220 TWh/yr, for river at 99 TWh/yr, and for ocean current at 49 TWh/yr.	The Igiugig Tribe in Alaska reduced dependence on imported fossil fuels with a community-owned RivGen hydrokinetic power converter [46]. Using clean energy sources increases the Tribe's resilience to climate change as well.
Ocean Thermal	OTEC systems generate power using the temperature differences in tropical and subtropical oceans. OTEC systems can be installed on floating ships or platforms to produce freshwater at a much cheaper price than other large-scale seawater technologies. They can also produce hydrogen for onshore energy production [69] and are capable of providing baseload, reliable power [67].	Not yet commercially viable [70].	The technical resource is high for ocean thermal at 540 TWh/yr [66]. While resource availability is large, less than 1 % is located near land and can be used with available technologies [66].	OTEC technology could limit effects on corals and reduce conditions for extreme weather like hurricanes by limiting temperature rise in the surface of the ocean. Further, OTEC's nutrient rich ocean water could support marine organisms and increase their uptake of atmospheric CO_2 [71].
Salinity Gradient	Salinity gradient technologies capture the chemical pressure differential between freshwater and saltwater in order to generate power. This differential is most often found where a river flows into the sea [67]. It can be used to power desalination plants—or produce freshwater [72].	Have mainly been used in experimental demonstrations [67].	Unknown.	Research by Brauns [73] suggests that seawater desalination could be accomplished using salinity gradient technology paired with solar energy.

Although the report does not explore MRE options, it notes the importance of using Sitka's existing energy resources to foster community economic development and reduce fuel imports "without over-dependence on limited hydroelectric capacity" (especially to meet growing heating demand) [92]. MRE potential was, however, explored in a 2012 Integrated Resource Plan conducted for the Southeast region of Alaska [93]. The report points out the significant environmental and project development risks (e.g., financing, transmission constraints, regulatory challenges) associated with MRE development that could hinder its overall feasibility but nevertheless highlights the need to continually track improvements in the cost and performance of emerging technologies, such as tidal, to support resource diversification and future energy needs [93]. A more recent study on renewable energy options for Sitka found tidal resources to be sufficient for baseload power production and more reliable than resources like solar for consistent power output in the critical winter months [79], yet especially prohibitive in terms of project development timelines (10 years) and cost (requires underwater transmission build-out, although close to existing utility assets) [94].

3.1.2. *San Juan Islands*

The San Juan Islands, an archipelago located off the state of Washington, are home to an abundance of biodiversity, which drive the county's thriving tourism industry [95,96]. Although farming and fishing were foundational to the economy pre-1970s, private services currently account for 67 % of nonfarm occupations, with leisure and hospitality consistently representing the largest industries on an annual basis [97]. Due to the geographic isolation of the islands, there is little opportunity for economic diversification, and this, coupled with highly seasonal tourism, has affected the labor force and unemployment rates. In April 2020, the unemployment rate in San Juan County reached 19.2 % but dropped to 3.6 % in the final months of 2021—consistent with the rhythm of the tourist season [97]. The isolated nature of the islands also spells challenges for its energy system, which until recently, had only one source of power: two aging submarine cables connecting the area to the mainland, both in need of costly replacements in the near future [98]. For this reason, the electric provider for the islands, Orcas Power & Light Cooperative (OPALCO), invested in a community solar farm and battery storage project to augment grid reliability, extend the life of the cables, and reduce peak load from the cables to save customers money [99]. OPALCO plans to extend this solar plus battery storage combination to create microgrids throughout the islands, but there remain concerns about the land footprint associated with energy development and whether solar can even meet the county's demand for power. As such, the utility is exploring other options in addition to solar, such as tidal, which has "the potential to be for [the San Juan Islands] what solar is for Arizona" and account for up to 50 % or more of local generation [100]. Much like Sitka, the San Juan Islands also contend with costly imports of fuel (mainly propane) for residential heating purposes. With the utility being charged $220,000 in 2018 for a single cold-weather electric purchase, efforts are also underway to increase household energy efficiency while encouraging customers to move away from fossil-fuel-based heating [100,101].

4. Data and methods

This study builds on recent research and advances in MRE technology and social acceptance literature, including their broadening application and policy integration, to leverage new energy investments for environmental and economic justice [102]. This study explores the compatibility of MRE technologies within the context of two U.S. coastal communities and provides a model for future MRE research and development that can reduce community vulnerabilities and improve socioeconomic outcomes amid a changing climate. To that end, the following questions inform the research design:

1. What vulnerabilities to the social, ecological, and economic well-being of coastal communities in the United States can be attributed to energy infrastructure and service deficiencies?
2. How can MRE technologies and related project planning address community vulnerabilities?
3. What contextual characteristics of coastal communities are critical for community-MRE compatibility?

To gain a grounded understanding of the socio-technical issues affect MRE compatibility within different community contexts, this study follows a mixed-method, exploratory approach to community assessment. In so doing, this study connects the pragmatic and constructivist orientations of recent community-based development research, which seek to value informant perceptions and experiences as knowledge and, in turn, understand how issues are socially constructed and contested (e.g., Rapid Rural Appraisal, Rapid Assessment Process, Appreciative Inquiry) [103]. Community assessment methods [104] increasingly require multi and transdisciplinary approaches, as evidenced in research on public health and medicine [105], ecological and biodiversity conservation [106], sustainable development [107], and more recently, community renewable energy [108]. Community assessment methods often integrate three key processes: (a) mapping the system to identify the breadth of issues and actors that construct the local context, (b) collecting data through multiple methods to represent a diversity of perspectives embedded in the system, and (c) analyzing the findings through iterative engagement between the researchers and, in some cases, research participants. This supports data triangulation and validation by providing multiple opportunities to reflect on and adapt the research strategy to meet community objectives. These research orientations and processes informed the following research methods:

4.1. Case identification and informant interviews

Given the exploratory nature of this research, non-random convenience and purposive sampling (see Miles & Huberman [109]) was used to identify informants within two case study locations: Sitka, Alaska and San Juan Islands, Washington. These locations were selected based on the knowledge and networks gained from past projects by the research team. This ensured researcher access to key informants within communities already pursuing strategic energy planning to address their vulnerabilities. Researchers contacted six key informants, and they each agreed to participate in an online interview. The informants represented local residents, non-governmental organizations (NGOs), and utilities who had different perspectives and could speak to broad, community-level developments, issues, and concerns related to MRE:

- San Juan Islands representative from the utility cooperative
- San Juan Islands representative from an environmental NGO
- Sitka representative from the municipal utility
- Sitka representative from an environmental NGO
- Sitka representative from an energy-focused NGO
- Sitka community member conducting MRE research.

Semi-structured interviews were conducted with the informants in June and July 2022 (average length = 51 min) [109]. They were audio-video recorded and transcribed with consent. Researchers introduced the goals of the research before asking questions that addressed four vulnerability themes identified in the literature: environmental change, community livelihoods and resource dependence, energy systems and reliability, and coastal management. Informants were asked to speak from their own experience and understanding of their community. Their responses dictated the order of the questions asked to facilitate a more natural discussion about community vulnerabilities and related development.

4.2. Qualitative interview analysis

Text from the interview transcriptions were coded following an iterative and inductive process, which included open coding, category development, and thematic coding [110]. During open coding, three researchers coded the six transcripts, with at least two researchers coding each transcript for comparison and member checking [11]. Open coding included labeling and describing emergent concepts using memos within the transcripts that related to the research questions. More than 150 codes and sub-codes were identified by the researchers. As a team, the researchers compared codes for overlap and theoretical relevance, grouping similar codes into categories and providing preliminary category labels in a spreadsheet. This process facilitated the development of five high-level themes (energy development, institutional relations, resource relations, resilience, and community values), which were collaboratively organized and defined in a summary codebook (Table 2). The high-level themes emerged from the way informants reframed and connected interview topics through interactions and scales that were salient to them. For example, informant responses to “management” questions were reframed both through specific relationships with formal and informal institutions as well as broader, systematic constructs like community values. In this case and others, there is a critical connection between themes. Researchers reviewed the original transcripts and codes to refine their memos in accordance with the codebook and selected illustrative quotes to aid interpretation of informant perspectives in response to the research questions. The results of the qualitative analysis are organized around these themes and quotes.

Table 2
Framework for coding and thematic analysis of interviews.

Theme	Example Codes	Definition
Energy Development	Renewable technology; supply and demand; cost and affordability; reliability; alternative systems; innovation; infrastructure; impact assessment; tradeoffs; feasibility	Characteristics, conditions, or impacts of alternative or renewable energy technology development, including current status, interactions with existing energy systems, and future community priorities or needs.
Institutional Relations	Governance structures; stakeholder roles; civic engagement; social networks; communication; trust; regulations and rights	Organization and outcomes of sociopolitical institutions and (in)formal partnerships. Their interactions and feedback influence civic engagement, collaboration, knowledge, and trust.
Resource Relations	Access; dependence; ownership; decision-making; knowledge and experience; geography; infrastructure; economics and industry; livelihoods	Community access to and dependence on the resources needed to address socioeconomic vulnerabilities and maintain their livelihoods and well-being. Resources may include natural resources, energy, food, housing, infrastructure, networks, information, knowledge, and democratic participation.
Resilience	Risk and vulnerability; adaptive capacity; diversity; redundancy; planning and development; innovation; growth; change; historical events	Events, actions, or characteristics that influence the structure and function of the social-ecological system, including community capacity to proactively plan and reactively respond to change despite geographic vulnerabilities or constraints.
Community Values	Independence; connectivity; self-reliance, sufficiency and determination; security; place identity; civic engagement; conservation; stewardship; openness; conflict; decarbonization	Perceptions, attitudes, or beliefs about the underlying value structure and definition of the community, culture, and local traditions. Multiple values may be referenced together, including where conflicting values create tension and affect community priorities or decision-making.

Researchers reviewed the original transcripts and codes to refine their memos in accordance with the codebook and selected illustrative quotes to aid interpretation of informant perspectives in response to the research questions. The results of the qualitative analysis are organized around these themes and quotes.

4.3. *Quantitative technical analysis*

While community values and vulnerabilities inform the compatibility of a given development strategy, technical analysis is needed to validate whether MRE can address those vulnerabilities. Researchers conducted a two-part modeling analysis focusing on grid infrastructure and load impacts of MRE deployment. Due to data availability constraints, the analyses focused on one MRE technology (tidal generation) in one case location (San Juan Islands). First, an infrastructure deferral assessment was conducted to understand how MRE integration can defer costly upgrades to the two submarine cables connecting the San Juan Islands to Lopez Island. This was done by comparing technological scenarios with different sizes and pairings of tidal generation and battery energy storage systems (BESS). Second, a load profile assessment was conducted to understand how MRE can support the community load profile and peak demands. Both assessments consider different types of technological compatibility with MRE. The deferral assessment considers integrating a BESS to enhance deferral benefits because local utilities, including in the San Juan Islands, are already investing in BESS to support critical loads during outages and improve local resilience. The load assessment considers integrating solar PV to enhance resource adequacy. A detailed explanation, including the deferral analysis methodology and modeling assumptions for these assessments are presented in Appendix A.

4.4. *Limitations*

This study offers useful insights and opportunities for future, more in-depth investigation to probe further into aspects that are not fully captured here. Although the research design carefully navigates known issues with community-based research approaches [111], there are limitations to the generalizability of findings—even with the limited number of study locations and key informants engaged for this study. Given the number of participants, the breadth of community perspectives was also limited. As such, this research only captures the positionality of specific stakeholders (namely local residents, NGOs, and utilities) on the topic of community-scale MRE development; future research should attempt to better understand the reaction to MRE development from stakeholders such as commercial resource users (e.g., fishers). Future research can also consider how different value streams associated with MRE accrue differently based on stakeholder perspective. Additionally, more comprehensive studies combining participatory appraisals and formal socio-technical assessments will be necessary to inform decisions on design and operation of actual projects.

Constraints with data availability also limited the technical analysis to the San Juan Islands community, and although results indicate promising MRE benefits there, the extension of a similar analysis to the Sitka community is necessary to understand the breadth and relative value effect of MRE deployment. Moreover, we do not comment on the costs of adding MRE tidal generation and other distributed energy resources (DERs), as this study is focused on the local benefits of key infrastructure. The inclusion of comprehensive costs of integrating DERs could be explored in future works. Given that the principal aim of this study is to offer initial insights into the ability of MRE technology to address coastal community vulnerabilities and energy security using a grounded research approach, the findings and recommendations here should be used as a basis for designing more comprehensive and place-based investigations.

5. Interview findings

Remote interviews were conducted via Microsoft Teams with six key informants from the coastal communities of Sitka, Alaska, and the San Juan Islands, Washington. This section provides the findings from the interviews condensed into five characteristic themes (energy development, institutional relations, resource relations, resilience, community values) (see Table 2).

5.1. *Institutional relations*

Energy issues can be connected to governance frameworks reaching far beyond what might typically be considered “energy policy” [112]. The nature of governance strategies, policy mandates, stakeholder engagement processes, and public civic participation opportunities influence the development of relationships between people and institutions that affect local priorities for energy development. These interactions might include formal or informal partnerships, development of social networks, and information or knowledge sharing practices. Outcomes from these interactions are key to understanding the attitudes of stakeholders and the ways in which institutional frameworks are constructed to facilitate (or not) bottom-up or grassroots organization, co-ownership and management of public resources, accumulation of local knowledge, social capital, and trust in government. Our respondents indicated that these qualities are important components of an engaged citizenry, as well as enablers of innovative energy design and alternative modes of development that achieve equitable benefits for the community.

Where citizens feel empowered to participate in decision-making, they are more likely to advocate for collaborative solutions to vulnerabilities, such as insecurities related to energy, food, transportation, or housing. Respondents in both locations connected higher education and affluence with greater levels of civic engagement. Interviewees from Sitka took pride in their community's focus on the importance of science and environmental education, while respondents from San Juan Islands reported that they have the highest number of non-governmental organizations (per capita) than elsewhere in Washington. A respondent from San Juan Islands viewed the potential development of marine energy as an opportunity for scientists and environmental groups to engage with energy developers to share knowledge and information while also affecting energy security:

> If there was potential to tap into marine energy, I would urge [developers] to connect with [local] scientists and environmental groups … segments of the community who could help to identify whether what they're considering would be a good fit in terms of our marine ecosystem. And if that proved to be true, I think they would get a huge amount of public support. I think we all recognize that that cable is a tenuous connection to our energy source on the mainland. And I think a lot of people would be happy for OPALCO to identify ways to have more energy independence (San Juan Islands, NGO representative).

Utility representatives, however, most frequently view their most appropriate role in a civic context as an “honest broker” [24]—providing alternatives and trade-offs once an objective is agreed upon by the community but hesitant to advocate for particular solutions:

> As the electric utility, it's not our job to lead, tell the community, “You need [infrastructure] here, you need it here,” because it's part of an overall community planning. And so, if you're banging on our door, you're kind of putting the cart before the horse. Because that's not what a utility company does. What's the cost justification that we have as a utility to put in a bunch of [electric vehicle] chargers when there is no revenue coming in and it raises their rates? And even if the chargers are free, unless there is the funding for transmission distribution substations to go with it, you may not be able to have it

> right away…there has to be either the funding for it from outside sources or the revenue projections to cost justify that investment (Sitka, utility representative).

Respondents viewed energy investments in their communities as important beyond providing electricity. Benefits of renewable energy were connected to adjacent sectors, such as technology, transportation, communication, education, housing, and food. Highlighting these interconnections can help illuminate social vulnerabilities and make wider policy implications clear for addressing multiple challenges through innovative and equitable energy development.

> The utility is public and…they're trying to think of themselves as energy people, not necessarily electricity people. They've got some cool projects around food security and other applications out for funding, so they're kind of working through how much to involve people and when (Sitka, community member).

> The price of fuel going up affects shipping, which affects the cost of food. Food security is a really big concern and a big issue for us, and a lot of different groups are working on food security issues, whether that's mariculture or encouraging gardening or subsistence gathering (Sitka, NGO representative).

Additionally, the historical relationship to Tribal governments was mentioned by respondents as being connected to natural resource use and development, particularly in southeast Alaska. Investments in infrastructure, including energy, were tied to legacies of broken trust and mistreatment of Indigenous populations by the U.S. government, and much work remains to remedy past injustices and ongoing racism:

> And it's amazing when I go into communities, we have conversations about energy, and I learned so much about awful, awful things that have been done to indigenous people in the communities. Oftentimes what I hear about is just double dealing, duplicitous dealing between governmental entities and their communities and just a total lack of trust and residual trauma that exists over time that doesn't go away because it hasn't been dealt with. They haven't been heard. There hasn't been an attempt to remediate those wrongs that were done (Sitka, community member).

Tribes are considered key partners in the push for renewable energy and MRE, as the land ownership structure, usage rights, and access to resources concern issues of tribal sovereignty in the San Juan Islands:

> There's not a lot of tribal-specific lands here, but there's fishing rights, there's usage rights, and then there's those other rights that we have to be respectful of (San Juan Islands, utility representative).

The relationships between municipalities and Tribal governments include formal channels to receive input and support for energy projects, as well as demonstrating shared values in the community that enable collaboration to work towards energy democracy [113]:

> I think they [Tribal government/community] might have a different perspective and I'm sure there are issues, but in terms of formal processes, they've got an established government-to-government relationship that's addressed at every city assembly meeting. Most organizations (e.g., Conservation Society, Forest Service, etc.) go to both governments, which seems like an established practice. (Sitka, community member).

In summary, the selected interview excerpts show how institutional relations enable or constrain energy development and resilience. Informants distinguished the current and desired roles of stakeholders. They acknowledged how those roles influence the value justifications for MRE developments and create tensions that cannot always be addressed through formal processes.

5.2. Resource relations

The extent to which communities can access various resources plays a role in their priorities for renewable energy development as well as overall social and economic well-being. Access to natural resources can provide economic security (e.g., marine-based livelihoods), while access to information and knowledge enabled by broadband internet and energy infrastructure can open connections to broader regional markets and economic systems that provide employment opportunities not available locally:

> I think giving people the opportunity to participate in the globalized economy, which would be a game changer, and I see that over and over and over again that it's not just the cost of energy, but it's the access to knowledge sharing networks and the access to good paying jobs that can be accessed via broadband (Sitka, community member).

> There's been a big push to expand access to broadband. And I think that's really changed the potential for people to be here [in San Juan Islands] full time and work remotely. (San Juan Islands, NGO representative).

Conversely, dependence on limited resources can constrict available opportunities for economic development and innovation while increasing costs of everyday commodities due to transportation needs. In our two interview locations, resource dependence compounded the vulnerabilities inherent in geographic isolation. Respondents viewed the potential for MRE development as one solution to the risks associated with their dependence on distant resources, for both affordability and independence value:

> We do see [off-island energy dependence] as a risk, but … we have at least two methods of getting power to the substation. So, in most submarine cable crossings we have two submarine cables, and that's just strictly for reliability and resiliency. If for some reason one of the submarine cables gets damaged, we're getting close to the limit of the one that's left. So, we have roughly 100 MW of threshold on both of our submarine cables individually. And so, for maintenance or accidents, outages, our peak end is 100 MW [Megawatt]. So, whatever we can do to have the generation source here and not rely on the mainland as much means we don't have to replace super expensive infrastructure (San Juan Islands, utility representative).

> Where [MRE] would appeal to Alaskans is that we're not dependent on something from the lower 48. Right now, a lot of Alaska communities are dependent on oil. We don't have oil refineries in Alaska, so the oil moves down to lower 48, gets refined, comes back up. It's just as expensive here as it is anywhere else. So, with that sense of independence that Alaskans have, I think marine energy would appeal to them on that level; and a lot of people live off the grid, so I think it's gonna appeal to that group too. (Sitka, NGO representative).

Communities are also dependent upon natural resources to sustain livelihoods and rural ways of life. Traditional natural resource-based industries (e.g., forestry, fishing, mining) rely on an abundance of resources to extract and transform into commodities to sustain rural economies. Due to local demographic and economic changes, extractive resource industries have recently given way to more service-based industries (e.g., tourism, charter fishing) that rely on natural resources in non-extractive forms. Although intra-regional migration and demographic shifts continually restructure the population, communities remain dependent on their resource-based amenities to support economic development and collective goals. Interview respondents viewed renewable energy, including MRE, as one opportunity to pursue common values-based goals of energy independence and environmental sustainability:

> I think [motivations for renewable development] are definitely practical, but also just wanting to take steps to do what we can to contribute to reducing our dependence on fossil fuels. And even hydro energy has its issues in terms of the impact to salmon and their access to spawning areas (San Juan Islands, NGO representative).

Additionally, (lack of) access to resources was a primary concern for community members in considering the feasibility of various energy development propositions:

> Hydroelectric technology works very well in almost every place in Southeast Alaska. You've got mountains, you've got rainforests, you've got valleys, you've got what you need in a very rough sense, to do hydroelectric in every community (Sitka, community member).

> Nobody's tapping the marine energy out here, so let's look into it. Let's see about the feasibilities... You can't say it's gonna be feasible at today's dollars and today's prices, but if you purchase it now and hedge it for later, you likely can make that bet (San Juan Islands, utility representative).

Interview excerpts labeled resource relations demonstrate how the proximity of resources present opportunities and barriers to energy development and resilience. Informants described how their reliance on spatially distant resources, such as oil, increases their vulnerability, and advocated for proactive planning that leverages non-traditional resources, such as networks and knowledge, to improve local access to resources in the future.

5.3. *Resilience*

The theme of resilience emerged as a key community characteristic that reflects perceived socio-ecological risks and vulnerabilities, as well as the community's ability to adapt to acute and chronic environmental changes. Researchers often define resilience as the ability of a community to maintain the structure and function of its social and environmental systems in response to a disturbance, such as natural disasters [114]. Respondents most frequently described resilience in the context of energy security and vulnerability, city planning, adaptive capacity, and diversity. Energy security refers to the reliable and affordable provision of electricity to customers:

> Overall, our goal as an islanded municipal utility is to provide the most cost-effective rates we can, bearing in mind that reliability and continuity of service is highest priority (Sitka, utility representative).

Achieving energy security increases the resilience of a community when there is redundancy built into the system to better absorb disturbances that may disrupt transmission:

> We have two hydroelectric facilities, and then we have a diesel standby plant, and generally we can operate on hydro, but sometimes we might have an avalanche or a landslide or something like that, that may take out our transmission line, and then we have to rely on diesel (Sitka, utility representative).

Respondents cited vulnerabilities that affect energy security, including geographic variability, infrastructure, costs and supply, reliability of service, and social relationships between community members and utility providers. Infrastructural vulnerabilities are related to the remoteness of respondent communities, which both affects the ability of utilities to provide reliable service and the cost of providing electricity to consumers based on available supply. Transmission line construction often necessitates development in pristine wilderness areas with little access, steep terrain, and variable topography. To overcome these vulnerabilities and increase community resilience amid uncertainty, utilities must have a diversity of energy sources to ensure supply adequately meets demand and provides a buffer against unexpected events. Additionally, the need for integrated expansion planning, distant grid connection, and/or diverse local generation and transmission services (i.e., microgrids) introduces complexity in achieving the support and buy-in from the community. For example, utilities are tasked with providing consistent and affordable service, and many respondents spoke at length about the appropriate role of the utility within the structure of city government and its relationship to community members. Respondents from Sitka perceived their publicly owned utility as more responsive to the needs of the community, which enables an adaptive approach to management that increases their adaptive capacity and resilience:

> The utility is owned by the community, and the structure of how utilities operate legally is really important. I think, based on plenty of evidence, that a utility that is municipally owned has an ability to bring about change more easily than utilities that are investor-owned or co-op structured utilities (Sitka, community member).

Interview excerpts about resilience focused on efforts to maintain energy security and reliability through infrastructure redundancy and adapt to environmental conditions or community needs as they change. As mentioned above, informants felt their resilience was dependent on the structure of institutions, such as utilities, and ability to access economic resources.

5.4. *Community values*

Coastal communities are economically dependent on natural resources, which in turn structures the value systems present within them. A common theme that arose from respondents was the idea that environmental or place-based values often conflict with economic or growth-based values. Since values are a latent concept reflecting fundamental principles at the individual level, they underpin each of our identified themes (i.e., institutional relations, resource relations, resilience, and energy development), yet often remain unacknowledged in community discussions, which can result in conflicting priorities in participatory decision-making processes. Questions of *how* to develop or grow tend to overshadow the normative question of whether the community *should* grow at all:

> People are concerned about the cost of housing and where we can develop. We can't really develop too much further than we've developed. There's not much space here. Most of it is owned by the federal government. So, there's a lot of talk about how to develop and where to develop and who should develop and how to make low-cost housing (Sitka, NGO representative).

In short, place matters, and communities are embedded within a nested sociocultural and environmental context that defines that place. How people relate to a place, then, defines the character of the community. When values come into conflict due to changing dominant industries, migration, resource insecurity, or development, policymakers face challenges balancing collective goals for energy independence, economic progress, natural resource conservation, integrative coastal management, and community resilience.

In our two study communities, respondents indicated that environmental values underpin other facets of decision-making: “Sitka is a very environmentally conscious place. We have kind of a pristine environment, and anything that we have to do has to be environmentally sensible” (Sitka, utility representative). Values that draw people to the natural amenities and access to nature enabled by coastal environments are also a primary motivation for many who live there: “People who live here, their quality of life is really influenced by the natural beauty around us and the quality of the marine ecosystem” (San Juan Islands, NGO representative).

In general, communities sought some level of agency and self-determination over decisions and policies that affect civic life (as opposed to a top-down, command and control form of governance) [115]. Citizens are provided opportunities to participate in civic processes through public meetings, ballot initiatives, elections, and other in/formal channels that determine pathways for economic development.

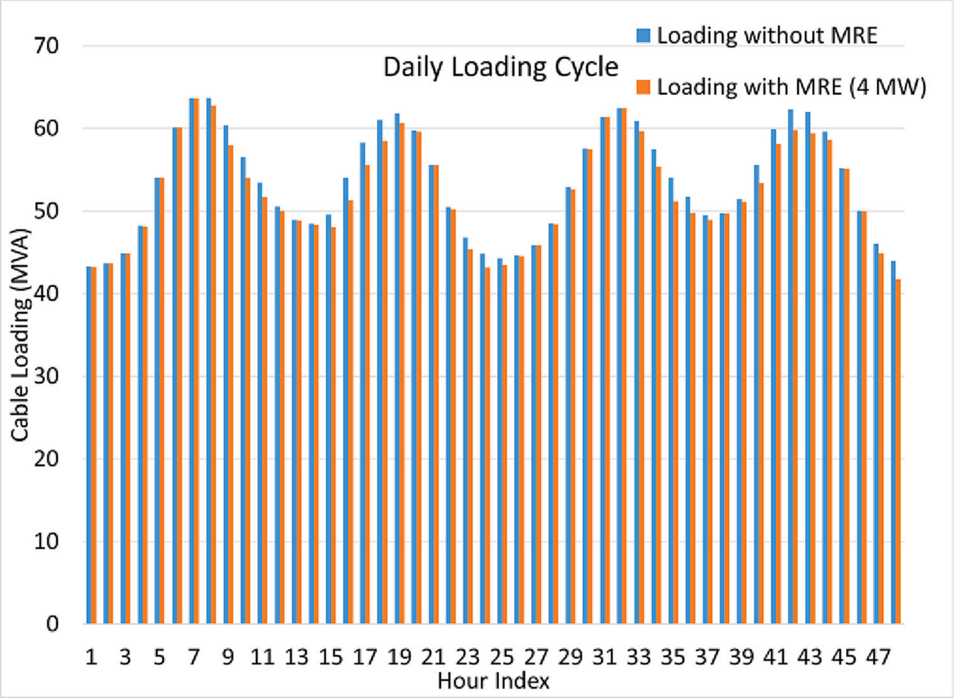

Fig. 1. Cable loading with and without MRE integration of 4 MW tidal generation.

Achieving common goals of energy, food, and housing security may necessitate actions, such as infrastructure development, that conflict with other environmental values.

> A transmission line would add [electricity] generation for Sitka and open up swaths of land for housing because there would need to be access roads. So, between that and the fact that the line would go through significant wilderness space that is a respite where people go and be in the great outdoors, those two aspects are things the city should be looking at (Sitka, community member).

Geographic, economic, social, and environmental vulnerabilities not only shape key challenges of coastal life but also influence community values and the lens through which community members prioritize and address related vulnerabilities. The concept of self-reliance cited by respondents emphasized shared values such as independence, agency, and self-determination—values that may conflict with community objectives that prioritize growth, development, and connection to broader economic systems.

Perceptions of and support for renewable energy development, such as MRE, are embedded within the value contexts and often conflicting priorities between environment and economics. Our respondents indicated an attitude of openness to new technology that might align with independence values but tempered such development with a concern for marine wildlife and ecosystems:

> For a lot of people, Alaska is just like this big, wide-open space, but every space is someone's favorite fishing place or some critical habitat for something. It's like, is this gonna be near kelp beds? Is this gonna be where lots of [species] depend on kelp? Or is this way offshore in shipping lanes? Is this gonna bother whales? I think those will be people's concerns about [MRE] (Sitka, NGO representative).

> There would definitely be support for OPALCO to identify sources of renewable energy they could provide through the grid that were not impactful to the environment and that provided us with some level, or maybe allowed us to be entirely self-sufficient in terms of our energy needs (San Juan Islands, NGO representative).

There were differences, however, in the ways our respondents prioritized their values. Utility representatives from Sitka and San Juan Islands viewed the primary value propositions of renewable energy as affordability, reliability, and safety. One respondent referred to “value stacking” as one solution to align community values with the utility mandate to provide service through cost-savings, efficiency, or asset maintenance and replacement:

> Grab whatever values you can from wherever you can. If it's peak shaving from the slightest bit of saving on the BPA [Bonneville Power Administration] bill, that's fine. That's a value. If it's deferral of replacement of assets, that gives life to a system that doesn't need to be replaced, which is cash in the end of it. And then it's the efficiency of not having to transport it here. There's many other efficiencies, and then all the same, we get to turn to our members and say we did the right thing as charged to do (San Juan Islands, utility representative).

This concept of value stacking was also referenced by a Sitka utility representative: “And we have been quite public recently that we're looking at all forms of renewables as and trying to rack and stack them to help determine what are the next most cost-effective energy resources for us.” In a practical example, the respondent mentioned opting for developing an “underground transmission line (as opposed to overhead) and making a gravel pathway over the top that can be used for recreational hiking and other things,” thus aligning multiple community values, efficiencies, and utility directives while simultaneously facilitating economic development.

In summary, interview extracts on community values overlapped other themes, with informants identifying and contextualizing value conflicts. They focused on how renewable energy development may support some local values, such as self-reliance, but endanger others, such as sustainability. Informants acknowledged that resolving values conflicts requires greater collaboration and consideration of tradeoffs and agency over decision-making.

6. Technical findings

Technical analyses were performed on grid infrastructure and load

Table 3
Life extension in years for varying levels of penetration of BESS and MRE (with darker green shading indicating higher value).

Life Extension in Years	**No BESS**	**BESS (0.25 MW/1 MWh)**	**BESS (0.5 MW/2 MWh)**	**BESS (1 MW/4 MWh)**
No MRE		2.2	4.8	9.4
MRE (1 MW)	4.4	6.5	9	14.2
MRE (2 MW)	8.4	10.9	13.6	19.1
MRE (4 MW)	16.9	19.8	23	29.2

Table 4
Deferral benefits in Million USD for varying levels of penetration of BESS and MRE (with darker green shading indicating higher value).

Million USD Benefits	**No BESS**	**BESS (0.25 MW/1 MWh)**	**BESS (0.5 MW/2 MWh)**	**BESS (1 MW/4 MWh)**
No MRE		0.084	0.184	0.355
MRE (1 MW)	0.168	0.247	0.34	0.531
MRE (2 MW)	0.318	0.41	0.509	0.706
MRE (4 MW)	0.628	0.731	0.8432	1.055

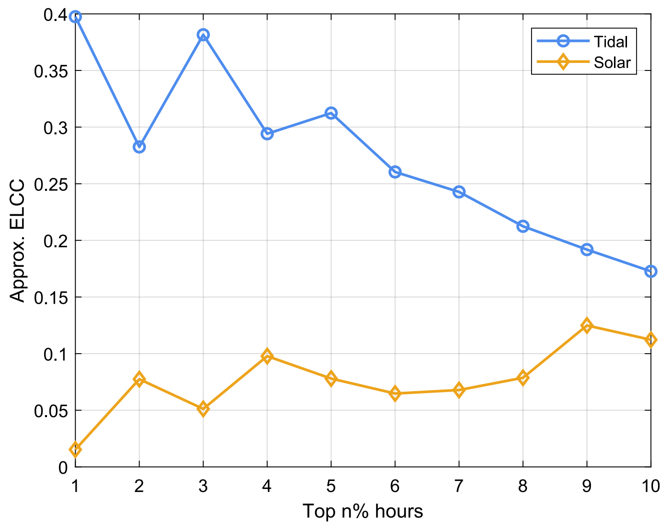

Fig. 2. Effective load-carrying capability of tidal and solar PV generators.

impacts of MRE deployment for the San Juan Islands. The results of the infrastructure deferral and the load profile assessments are provided below. Additional information on the methodology and modeling assumptions for these assessments are included in Appendix A.

6.1. *Infrastructure deferral assessment*

Submarine cables have a lifespan of approximately 40 years at the rated loading condition and cost approximately $5 million per mile to install, so deferring the near-future replacements of the two cables that currently supply power to the area spells substantial cost savings for the utility and the San Juan Island customers. MRE can do this by providing power locally, rather than relying on imported power that comes through the area's aging grid infrastructure. The dispatchability of integrated battery storage can further enhance the potential benefits associated with infrastructure deferral (by storing and discharging

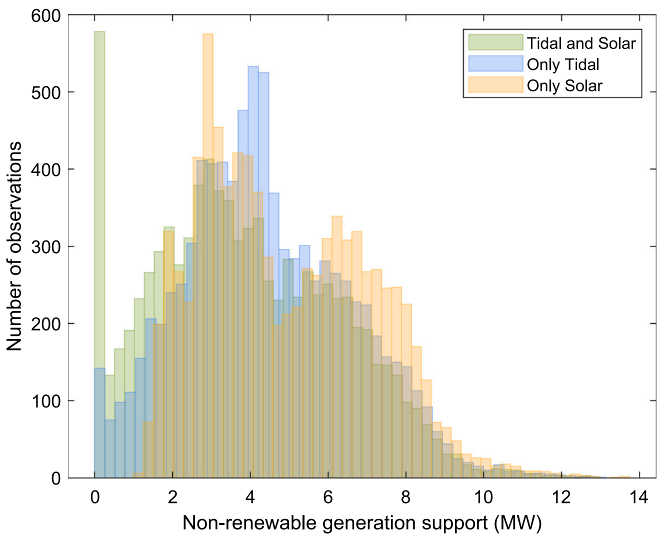

Fig. 3. Histogram of power import from non-renewable resources under varying portfolios of on-site renewables.

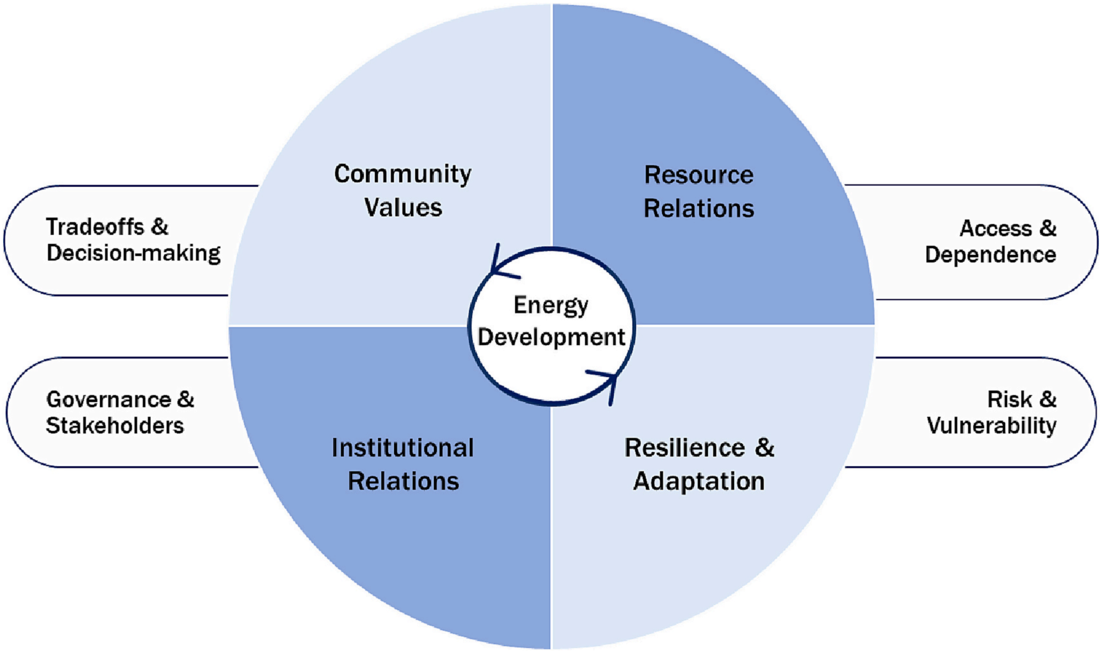

Fig. 4. Conceptual framework for community vulnerabilities and values analysis
The interview themes represent different scales and levels of interaction. Institutional and resource relations influence community values and resilience, which in turn, set conditions for energy development.

power in the local distribution system when needed, relieving the grid strain caused by long-distance power delivery).

The deferral of cable investment is therefore achieved by reducing the net load transported by the cable. As shown in Fig. 1, the integration of marine tidal power may reduce the electrothermal stress on the submarine cables, especially hours with sudden spikes in load, and hence extend the economic life. In this analysis, a tidal generator of 4 MW peak power was assumed, combined with the tidal generation potential time-series obtained using the resource characterization procedure conducted in Yang et al. [116].

With BESS integration, cable deferral benefits become greater. The highest level of benefits is demonstrated with the penetration of 4 MW MRE with 1 MW/4 MWh BESS, as shown in Tables 3 and 4. This combination yields a cable life extension of nearly 20 years vis-à-vis reduced operational strain on the infrastructure, representing nearly $1.1 million USD in present value. In all cases shown, the addition of MRE and BESS produces value.

6.2. Load profile assessment

While infrastructure deferral is a potentially appealing value stream for energy development, the justification for investing in energy technology is typically to access or provide cost-effective power (that may also deliver a number of grid co-benefits). The financial vitality of energy projects can rest on their ability to serve a customer or community need; if a generation source is ill-suited to the energy profile of a community and fails to reach needed objectives, it may be a poor investment choice, no matter how well-aligned such development is with community values and characteristics.

To understand the inherent demand supporting potential of on-site MRE resources, effective load-carrying capability (ELCC) is used as the metric. ELCC enables us to understand the potential of a new generator to serve incremental load (this was calculated for both MRE and solar PV). While actual ELCC calculation is quite resource intensive, a simple load time series-based approach can be used to approximate this metric. In this analysis, the capacity average capacity factors for a generator for the top n% demand hours is used as a proxy for the ELCC metric of that generator [117]. Through this analysis, holding a range of 1–10 % for ***n*** (in increments of 1 %), we find that the approximate ELCC of tidal generators is higher than solar generators (please see Fig. 2 for more details). This can be attributed to the persistent and periodic nature of the tidal resource.

Although tidal power has a greater ELCC than solar, results suggest that when energy import requirements are accounted for, they provide greater value together than as standalone resources. Owing to their location, the San Juan Islands rely on power imported from the mainland grid to meet the fraction of its energy needs that cannot be supplied through on-site renewables. The submarine cables that provide this power are not only aging and require costly maintenance, but they can face service interruptions during extreme weather events such as storms and hurricanes. Even during normal conditions, these imports can also be impeded by factors such as scheduled maintenance and upstream contingencies within the mainland grid from which the power is being imported. Having on-site renewable generation can lessen the costly import requirement. Considering this power import requirement under three scenarios—(1) only on-site solar PV generation, (2) only on-site

Table 5
Community energy objectives that emerged from interview analysis.

Community energy objective	Description
Energy Security	Increasing energy quality and reliability, supporting seasonality in peak demand, increasing energy self-sufficiency, minimizing mainland energy reliance, increasing energy portfolio diversification, supporting local energy development
Energy Affordability	Reducing energy cost, decreasing reliance on expensive fuels (e.g., diesel)
Energy Resilience	Increasing redundancy, reducing system disruptions and vulnerabilities
Environmental Sustainability	Maintaining environmental integrity and natural resource conservation, protecting marine health, supporting decarbonization
Economic Growth	Increasing energy capacity, supporting rural development, enhancing community well-being, supporting local economic activity

tidal generation, and (3) both on-site solar PV and tidal generation—we find the greatest benefit when tidal and solar are used together, as shown in Fig. 3 below. However, the histograms of the import requirements under the three aforementioned scenarios (across 8760 h of a representative year) show that, compared to solar, tidal resources can more reliably reduce the power import requirement.

7. Discussion

Energy development served as the guiding principle for this research, and it informed our analytical approach, which addresses the bidirectional feedback between community characteristics (e.g., resource relations, institutional relations, community values, resilience) and marine energy development potential (Fig. 4). In other words, community characteristics not only influence a community's need for renewable energy development but also their response to it. When asked about these characteristics, community representatives frequently cited place-based values that were informed by institutional relations and resource relations. These values and relationships affected the perceived vulnerability, resilience, and adaptive capacity of communities and, in turn, the energy objectives they prioritized (Table 3).

Geography was one community characteristic essential to understanding energy development objectives. The isolated nature of Sitka and the San Juan Islands communities means they are exposed to natural hazards, such as landslides and tsunamis, and they are dependent on mainland energy sources. Their exposure to natural hazards was cited as a potential vulnerability that can decrease the reliability of energy supply and community capacity to respond to related outages. Similarly, their dependence on mainland energy sources was perceived to affect not only the reliability but also the cost of energy supply, which prompted community support for energy solutions that addressed energy security and affordability. As a result, these communities cited energy security and resilience as primary energy development objectives. MRE is well-positioned to meet these security and reliability objectives through local power production, which also reduces the strain placed on transmission and distribution systems to carry power over long distances. Technical analysis results suggest that any level of MRE deployment (up through 4 MW) in the San Juan Islands can limit this type of strain by reducing the load carried by outdated submarine cables connecting the islands to the mainland grid.

The life extension of such expensive grid infrastructure via MRE development can potentially bolster energy security, resilience, and affordability objectives by providing local power and deferring upgrade costs that would otherwise be absorbed by ratepayers. Results suggest deferral savings of over $1 million USD with the max-benefit scenario of 4 MW MRE with 1 MW/4 MWh BESS. The development of MRE technology can also add redundancy to the system to better insulate against power transmission disruptions, including those caused by extreme weather events, ultimately enhancing energy security and resilience for community members.

Respondents indicated that energy development in their communities provides benefits beyond energy security and resilience, connecting development potential with energy affordability and vulnerability reduction. For example, high fuel prices affect the cost of shipped goods (e.g., food in Sitka), which is further compounded when considered alongside the increase in housing cost and decrease in housing availability. In San Juan Islands, the influx of amenity-migrants has introduced affordability and resilience concerns as the demand on the electric grid and need for housing has increased. Although energy development potential can be constrained by land availability, Sitka and San Juan Islands representatives acknowledged how energy development could catalyze new development of roads, which would provide more access to land for housing and meet the additional community objective of economic growth. In other words, MRE solutions address more than just technical vulnerabilities associated with energy supply—they can also reduce intersecting socioeconomic vulnerabilities (Table 5).

Geographic factors also influence another community characteristic frequently cited by respondents—resource relations. Resource access underpins the technical feasibility of MRE solutions, both in terms of access to physical resources needed for operation as well as the knowledge resources needed to connect MRE solutions to broader regional markets, systems, and opportunities. However, dependence on limited resources (due to geographic isolation) can constrain opportunities for economic diversification while increasing the costs of everyday needs like power and fuel. In both communities, respondents viewed MRE development as one solution to the risks associated with their dependence on distant resources, indicating energy development could be a viable pathway for pursuing the energy objectives of affordability and security. The cost of infrastructure and related transport of fuel and power are barriers to meeting energy objectives in these communities, so access to resources that provide both economic and energy security play a critical role in the viability of MRE development as a solution. The technical analysis results corroborate this idea, highlighting how a fairly consistent yearly tidal profile and high ELCC can help address the San Juan Islands' winter peaking load and thereby decrease reliance on mainland support through imports of fossil fuels. Although the ELCC of solar is less than that of tidal, the load profile assessment suggests that these two technologies are stronger together than apart; when combined, they are able to support load more reliably, at a greater number of hours per year, than as standalone resources.

Respondents from Sitka and the San Juan Islands communities indicated support for energy developments, such as MRE, that could increase their energy self-sufficiency; however, they also perceived a tension between increasing their independence and maintaining the economic growth associated with industries, such as tourism and recreation, which increasingly rely on virtual and physical connection to other communities. These values conflict with support for traditional, resource-based livelihoods and the related energy development objective of environmental sustainability. As communities redefine their approach to resource dependence, the opportunity for “constructive dialog and collaboration, or intra- and inter-community power struggles and conflict emerges” [118]. Further, researchers have shown that rural communities tend to support both economic and environmental goals simultaneously, indicating a “value dissonance” where trade-offs and relative development preferences depend on other variables, such as the community's age structure and proportions of long-term residents to newcomers [119]. Given their economic dependence on natural capital, Sitka and San Juan Islands respondents suggested environmental stewardship was foundational to civic engagement and decision-making processes regarding energy development. MRE development may therefore align with community values of independence and self-sufficiency but also conflict with preservationist perspectives that concern negative effects of technology development on marine wildlife and ecosystems. Utility representatives suggested these conflicts can be resolved through conscious efforts to value-stack. For example, they highlighted the ways MRE development can increase affordability, grid reliability, and system safety while still supporting environmental stewardship.

Finally, local utility and governance structures as well as related opportunities for civic engagement were community characteristics that affected the energy development objectives. Community MRE potential depends on the strength of institutional relations and networks because they dictate community capacity to understand and navigate their energy security needs and economic growth potential within the bounds of the current system. For example, multiple respondents acknowledged a community-ownership model could encourage the cooperation and collaboration needed to address diverse energy challenges and objectives while lowering upfront investments through cost-sharing. Empowering citizens through participatory decision-making and knowledge sharing processes makes them more likely to support MRE adoption. Further, respondents in both communities indicated that strong educational ties within the institutional network not only increased civic engagement but also the capacity to reduce vulnerabilities and increase energy resilience and environmental sustainability.

8. Conclusion

Given the modular nature of many MRE technologies and the proximity of island and coastal communities to vast ocean energy resources, MRE is well-suited to play a key role in local energy futures [3]. Much uncertainty remains, however, on how to best achieve community-based goals for resilience planning and equitable development that are consistent with the community's values. Our results suggest that MRE deployment potential is greater when strategic development and community-level visioning are aligned with community priorities. Moreover, our findings indicate that a key priority to resolving values-based conflicts around energy and economic development should be ample opportunity for engagement between citizen-led coalitions and various civic organizations, such as utility companies and city government. Bottom-up or grassroots participation in development decisions tends to engender greater trust than top-down directives aimed at singular values (e.g., economic growth) or simply regulatory compliance. As encapsulated in this quote from Jim Cavaye [17]: "…communities that are successful at community development are those that do not necessarily have greatest access to resources or expertise. They are communities that are inherently good at reconciling or managing conflict over community values."

Place-based values—particularly when informing questions of how to grow and make decisions—ultimately influence the way community members prioritize and address geographic, economic, social, and environmental vulnerabilities, which feeds into their perceptions of and support for marine energy development solutions. Likewise, the unique blend of economic, social, environmental, and technical vulnerabilities present in a community affects the suitability of MRE technologies to address the unmet needs created by these vulnerabilities. Given the nascent state of MRE implementation in the United States, coastal communities such as Sitka or San Juan Islands can serve as a "proving ground" through innovative pilot programs designed to assess technological, economic, and social-ecological viability of MRE systems at a micro scale. Commercial developers, utilities, regulators, and state and federal agencies can then consider scalable solutions to broader energy problems by integrating the place-based lessons learned from rural, coastal environments to achieve ambitious carbon reduction goals at a national scale. Greater investments, however, may be needed to realize this vision through technical assistance grants and other innovative sources of funding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Quantitative technical analysis

An infrastructure deferral assessment and a load profile assessment was conducted to understand how marine energy can support the San Juan Island community load profile and peak demands. A detailed explanation of the deferral analysis methodology and modeling assumptions for the load profile assessment are presented below.

A.1. Infrastructure reliability/deferral assessment methodology

Laying new submarine cables to meet load growth, serve reliability purposes, or perform any undersea maintenance are highly cost and time-intensive tasks. Therefore, being able to defer investment in submarine cables by extending their economic life and/or reducing maintenance needs by managing stress on the cables has significant financial benefits. To support the investment decisions of MRE, the deferral benefits of MRE-induced cable life reduction were demonstrated via scenario analysis (Fig. A-1). This modeling exercise considered a range of tidal power generation and battery energy storage system (BESS) size pairings to gauge the breadth of deferral benefits possible to the San Juan Islands community. Scenario runs consisted of various size and technology pairings (e.g., 1 MW MRE + no BESS, or 1 MW MRE + 1 MW BESS).

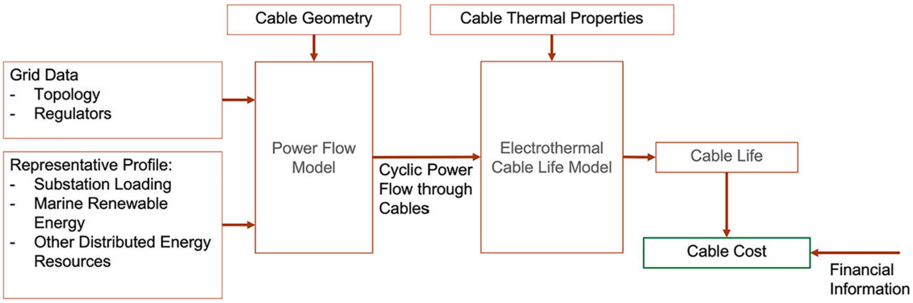

Fig. A-1. Overall methodology of the cable deferral procedure.

The overall methodology for calculating the cable life and eventually the benefits from deferring the cable is shown in Fig. A-1. The following steps are performed to calculate the cable life:

1. Collect information on the load data (Substation Load (MW) time series), cable geometry (Insulation level and manufacturing datasheet), and grid topology (transmission lines location etc.),
2. Collect local generation time series data, e.g., MRE generation (tidal power generation (MW) time series) and other DERs (e.g., Solar PV etc.)
3. Run a power flow study model to obtain losses, reactive power, and the overall power loading of cables.[2]

   Use power transfer across cable to calculate the cable stresses, impact on its life reduction using the following method: The approach for calculating cable life is adopted from [114], where an electrothermal life model estimates the life of an insulated cable when subject to a given loading cycle, or power transfer profile through the cable, that exposes the cable to electrical and thermal stress. The model incorporates a probability of cable failure in the estimation process and determines the life at a given design failure probability. The model is a replica for an accelerated aging tests that are first performed on mini-cable samples to estimate life model parameters which is then extrapolated to represent an actual cable's life-time as:

$$t_p = (-log(1-P_T))^{\frac{1}{\beta}} \cdot \alpha_0 \cdot \left(\frac{E}{E^0}\right)^{-(n_0 - b \cdot cT)} e^{-B \cdot cT}, \tag{1}$$

where t_p is the life of the mini-cable sample, P_T is the failure probability at which the test specimen life is determined, β is the shape of the Weibull distribution, α_0 is the life at 63.2 % failure probability, E is the electric field E^0 is the electric field below which aging is negligible, B is the ratio of activation energy of the main thermal degradation reaction to the Boltzman's constant b is a parameter that rules the synergism between electrical and thermal stress, cT is the thermal stress determined using the ratio $(\frac{1}{T_0} - \frac{1}{T})$, with T_0 being the absolute temperature of the rated cable design and the $T = f(I)$ denotes the estimated cable temperature, represented as a function of current I flowing across it – which can be calculated using multiple methods e.g., thermal resistance method of [114], and n_0 is the voltage endurance factor at $T = T_0$. The estimated life in (1) is translated to the actual cable's life (L_D) using the expression below.

$$L_D = t_P \left(\frac{-log(1-P_D)}{-Dlog(1-P_T)}\right)^{1/\beta} \tag{2}$$

where D is the enlargement factor to extrapolate life estimation from mini-cable to actual cable, and P_D is the design failure probability. The factor D could be approximated as shown in (2) where l_D, r_D, and l_T, r_T are the length and radius of the actual conductor, and the mini-cable sample, respectively.

$$D \approx \left(\frac{l_D}{l_T}\right) \cdot \left(\frac{r_D}{r_T}\right)^2 \tag{3}$$

Given that these cables are exposed to a loading cycle (typically 24 h or daily load cycle), loss of life fraction (LF) of a cable is for each time interval in that duration. Consider the loading cycle of width t_D (24, if daily cycle) contains N number segments. Then, LF for the i^{th} number segment of can be expressed as:

$$LF_i = \frac{t_D}{L_D \cdot N} \tag{4}$$

According to Miner's cumulative damage theory [120], the sum of all life fractions lost should yield 1 at failure. Therefore, total number of cycles before failure could be estimated using:

$$K = \left(\sum_{i=1}^{N} LF_i\right)^{-1} \tag{5}$$

The summary of the model (1)–(5) is as follows. Eq. (1) translates thermal loading cycle (current flow) into probabilistic life impact on the cable. Eq. (2) converts this impact into equivalent life spent Eqs. (4) and (5) use Miner's rule to map the life spent for the loading cycle to estimated remaining life.

4. Using the life-time of the cable extended, the cable deferral benefit was calculated using the present value method, where:

$$\mathrm{c}_{\mathrm{inv,base}}(\$) = \mathrm{c}_{\mathrm{cable,base}} \cdot (1+\alpha)^{\mathrm{t}_{\mathrm{now}} - \mathrm{t}_{\mathrm{base}}},$$

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[2] A power flow model representing the sub-transmission system of OPALCO was developed to estimate the losses and power flow across the cables. Inputs to these models include grid data, time-series information on the load, and distributed generation (such as solar PV), along with BESS operational models. Any open-source power flow modeling software (e.g. OpenDSS [116]) could be deployed for this, which can accept inputs such as cable insulation thickness and material, conductor geometry, and rated operating conditions to estimate cable resistance and inductance. These values are then utilized in the power flow model to calculate realistic power flow across the cable. The modelled submarine cable is a 69 KV XLPE (Crosslinked Polyethylene) submarine cable, using the specification obtained from its design data sheet.

along with the investment value of cable at end of its life:

$$c_{inv,eol}(\$) = c_{inv,base} \cdot (1+\beta)^{t_{eol}-t_{now}}.$$

Using the same calculation method, the investment value of cable at deferred life is given as:

$$c_{inv,def}(\$) = c_{inv,base} \cdot (1+\beta)^{t_{def}-t_{now}}.$$

With the above investment values, the present value of cable investment without deferral:

$$NPV_{cable,non-deferred}(\$) = \frac{c_{inv,eol}}{(1+\gamma)^{t_{eol}-t_{base}}},$$

and with deferral is calculated:

$$NPV_{cable,deferred}(\$) = \frac{c_{inv,def}}{(1+\gamma)^{t_{def}-t_{base}}},$$

Resulting in net cable deferral benefit of:

$$Benefit_{Cable-deferral}(\$) = NPV_{cable,deferred} - NPV_{cable,non-deferred}$$

The explanation of the above-mentioned variables along with their assumed values are described in Table A-1.

Table A-1
Variables used for calculating deferral benefit.

Variable	Explanation	Value
$c_{cable,base}$ (\$)	*Cost of cable at the time it was purchased*	\$13,900,000.00
α	*percentage inflation during time of cable purchase till now*	*3.25 %*
β	*percentage inflation for years beyond current year*	*4 %*
γ	*percentage cost of capital*	
t_{now} (*year*)	*Current year*	*2023*
t_{base} (*year*)	*Year of purchase of the cable*	*2021*
t_{eol}(*year*)	*Cable end of life year, year of installation + cable life*	*2057, (2017 + 40)*
t_{def} (*year*)	*Cable end of life year with deferral, year of installation + cable life + years deferred*	*Resulted from life in years determined from (1)–(5)*

A.1.1. Data and assumptions

The modeling assumptions used to model cable life is demonstrated as follows. Cable specifications deployed in the power flow study is obtained using assumptions listed in Table A-2. Table A-3 shows the electrothermal cable life model assumptions, from which a representative fitted cable life model is shown in Fig. A-2.

Table A-2
Cable specification.

Parameters	Values
Length	2.78 miles
Conductor Size	350 kCM
Conductor Diameter	15.7 mm
Insulation Thickness	16.5 mm
Rated Current	460 A

Table A-3
Electrothermal life model parameters.

Parameters	Values
E^0	5.5 kV/mm
E	6.25 kV/mm
T^0	284 deg. K
α^0	1.4×10^{15}
b	4308
B	12,937
n_o	18.8
P_D	0.05
P_T	0.632

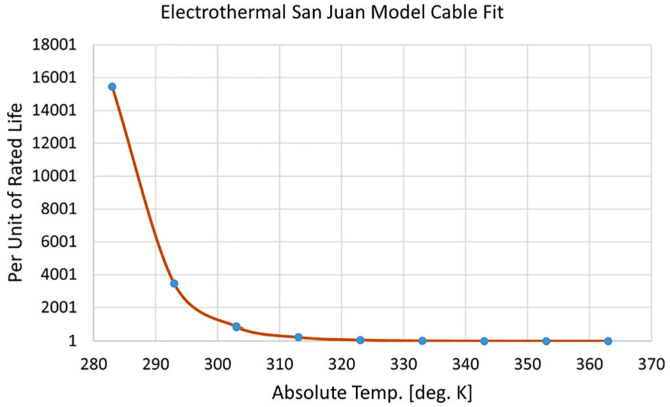

Fig. A-2. The electrothermal cable model assumption– *The nominal cable temperature is assumed at 283-K or 10-C (corresponding to cable temperature in winter times),* i.e.*, the life is approximately 15,500 times the rated life at 363-K. Using this model, the loss of life is determined as the operating temperature changes due to its power transfer loading.*

The load data, cable geometry, grid topology, and combination of MRE and other DERs were used to generate a power flow study model.[3] For this work, a sub-transmission model of OPALCO was created and power flow across all cables in the network was calculated. Based on different integration levels of MRE and other DERs, different power transfers were obtained. A steady-state power flow simulator tool was used to conduct this power flow study. With this, an accurate estimation of the losses, reactive power, and the overall power loading of cables can be reached. An electrothermal cable life model[4] was used to calculate the cable life extension or reduction, given the assumption of nominal cable life. With different technology scenarios, different cable life extensions were calculated, which yielded a range of cable operation costs and associated value benefits of deferring cable life.

With available resource data from the San Juan Islands area, tidal power generation profiles were generated. These tidal generators were assumed to feed into the San Juan Island Substation to reduce the net demand of the load transported to the island customers. Aggregated power of all tidal generators for hourly time resolution was determined to be sufficient for this analysis. Fig. A-3 shows the tidal power generation profile (scaled to nominal power) assumed for this study. The hourly community load (recorded at the substation) was also incorporated in the power flow model.

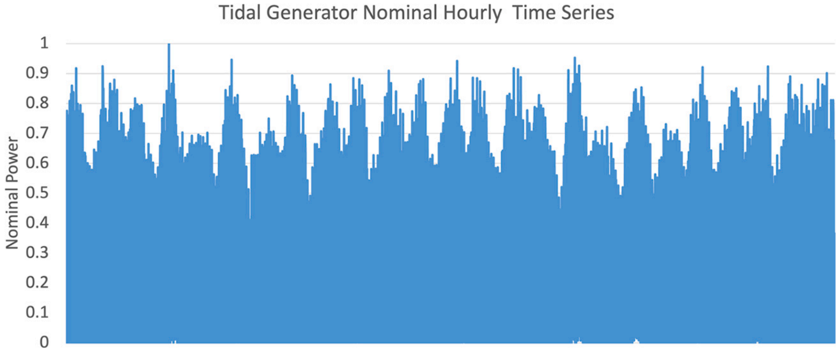

Fig. A-3. Assumed tidal generation profile for MRE integration scenarios, obtained from the resource characterization of locations around the San Juan Islands.

Resource assumptions were also made for the BESS integration scenarios. We assumed a utility-scaled Li-Ion battery with aggregated modelled charge/discharge efficiency and energy and power ratings of 1 MW/4 MWh, 0.5 MW/2 MWh, and 0.25 MW/1MWh. An example of the assumed daily charge/discharge profile of a 1 MW/4MWh BESS is shown in Fig. A-4.

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[3] A power flow model representing the sub-transmission system of OPALCO was developed to estimate the losses and power flow across the cables. Inputs to these models include grid data, time-series information on the load, and distributed generation (such as solar PV), along with BESS operational models. Any open-source power flow modeling software (e.g. OpenDSS [116]) could be deployed for this, which can accept inputs such as cable insulation thickness and material, conductor geometry, and rated operating conditions to estimate cable resistance and inductance. These values are then utilized in the power flow model to calculate realistic power flow across the cable. The modelled submarine cable is a 69 KV XLPE (Crosslinked Polyethylene) submarine cable, using the specification obtained from its design data sheet.

[4] The life estimation engine was built based on the approach presented in [114], where an electrothermal life model estimates the life of an insulated cable when subject to a given loading cycle, or power transfer profile through the cable, that exposes the cable to electrical and thermal stress. Also defined as a multi-stress model, it considers the impact of thermal and electrical stress simultaneously. The model incorporates a probability of cable failure in the estimation process and determines the life at a given design failure probability. The Weibull distribution function was used to fit the life model. Per the electrothermal model employed in this paper, it is held that at 283-K or 10-C (corresponding to cable temperature in winter times), the life is approximately 15,500 times the rated life at 90 °C, and exponentially reduces as operating temperature increases and converges to rated life at 90-C or 363-K.

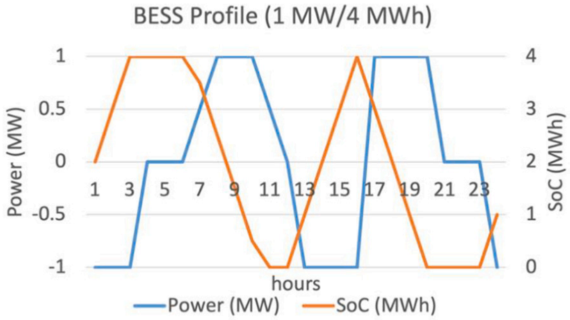

Fig. A-4. BESS profile used for BESS penetration scenarios.

We ultimately ran three main cases with varying levels of MRE (1 MW, 2 MW, and 4 MW) resources in the San Juan Islands and their impact on cable life deferral. The nominal tidal power profile shown in [115] [114] [116]Fig. A-4 was scaled to represent the peak power production of 1 MW, 2 MW, and 4 MW. Similarly, the 1 MW/4 MWh BESS charge/discharge profile of Fig. A-4 was scaled to represent scenarios for 0.5 MW/2 MWh, and 0.25 MW/1MWh.

A.2. Load profile assessment methodology

The extraordinary high capital costs of energy development cannot typically be justified without a need for that development. In other words, there is little incentive to invest in a particular technology for distributed use unless it adequately serves a community's load profile. Even if community values and characteristics are well aligned with MRE-driven objectives such as energy security, resilience, and economic growth, technological deployment may not be financially feasible without some guarantee that the technology can sustain peak loads and resource adequacy needs. In order to understand the degree to which MRE can do this, a load profile assessment was conducted. The modeling exercise considered scenarios with standalone MRE deployment and MRE paired with solar PV to see how well these resource profiles aligned with community electric demand.

A number of assumptions were made to conduct this assessment. The OPALCO load was rescaled to reflect the peak load of the San Juan Islands (13.75 MW). Note that the load here is winter peaking in nature. Four locations near the San Juan islands were selected based on resource potential for tidal energy development. In each of those locations, a 1.5 MW tidal energy turbine was assumed to be installed, thereby causing the net cumulative tidal capacity to be 6 MW. For each of this turbine, cut-in and cut-out speeds of 1 and 3.5 m/s are assumed. The tidal velocities, obtained from [115] were converted to tidal energy through a first-order model, as in [111]. A representative profile of solar energy generation in the San Juan islands was also assumed, with solar expected to be sparsely available during daytime hours of the winter season. In comparison, tidal energy is expected to be largely periodic, more consistent, and more uniformly available across the year. The peak capacity for the cumulative pool of solar-based generators was input as 2.5 MW (Fig. A-5).

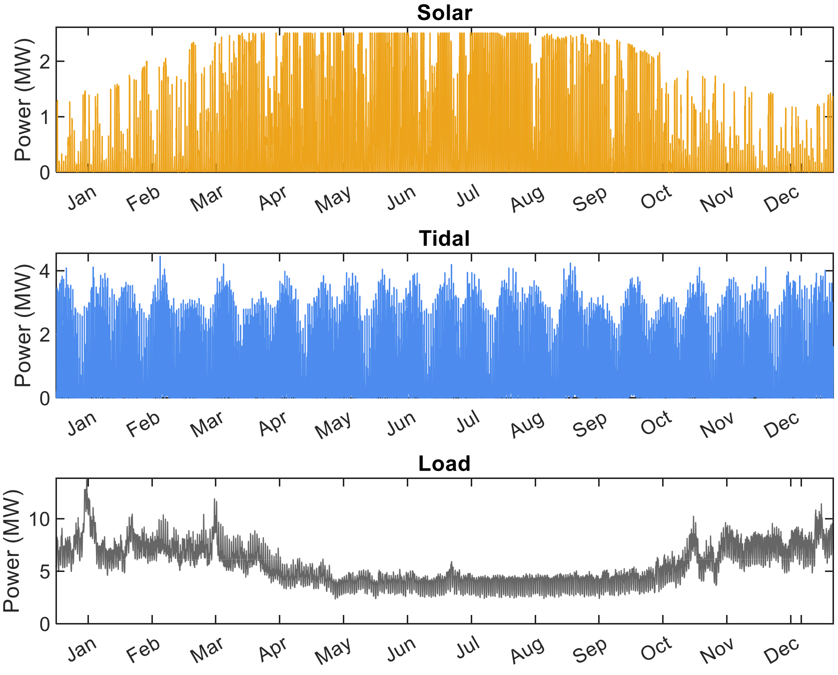

Fig. A-5. Representative solar, tidal and load profiles for the selected case study in San Juan Islands, WA.

The effective load carrying capability (ELCC), a standard reliability metric used to understand the potential of a new generator to serve incremental load, was applied in this analysis. We used a data-driven method similar to that of [111] to approximate the ELCC of both tidal and solar PV generators.

Under this method, the top n% of the peak demand hours were selected from an hourly dataset of a typical year, and the average capacity factor for the added generation resource across those selected hours was treated as the approximate ELCC.

After we approximated the ELCC value of each resource, we considered the power import requirement from non-renewable resources within the island power system under three scenarios: (1) with only solar resources available for onsite renewable generation, (2) with only tidal resources available for onsite renewable generation, and (3) with both solar and tidal resources available for onsite generation.

References

[1] K. Riahi, et al., Chapter 17: energy pathways for sustainable development, in: T. B. Johansson, N. Nakicenovic, A. Patwardan, L. Gomez-Echeveri (Eds.), Global Energy Assessment: Towards a More Sustainable Future, Cambridge University Press, Cambridge, UK and New York, USA, 2012, pp. 1203–1306.

[2] L. Creel, Ripple effects: population and coastal regions, in: Population Reference Bureau, Population Reference Bureau, 2003.

[3] R. Manasseh, S. Sannasiraj, K.L. McInnes, V. Sundar, P. Jalihal, Integration of wave energy and other marine renewable energy sources with the needs of coastal societies, Int. J. Ocean Clim. Syst. 8 (1) (2017) 19–36.

[4] Participatory Methods in Community-based Coastal Resource Management, International Institute of Rural Reconstruction, Silang, Cavite, 1998.

[5] D.C. Thomsen, T.F. Smith, R.W. Carter, G. Mayes, Defining community: understanding the meaning of 'the community' in coastal zone management, Journal of Coastal Research, vol. SI (56) (2009) 1316–1319.

[6] M. Wolsink, Wind power implementation: the nature of public attitudes: equity and fairness instead of 'backyard motives', Renew. Sust. Energ. Rev. 11 (6) (2007) 1188–1207.

[7] J. Blythe, et al., Frontiers in coastal well-being and ecosystem services research: a systematic review, Ocean Coast. Manag. 185 (105028) (2020) pp.

[8] M. Lange, V. Cummins, Managing stakeholder perception and engagement for marine energy transitions in a decarbonising world, Renew. Sust. Energ. Rev. 152 (2021), https://doi.org/10.1016/j.rser.2021.111740.

[9] K. Reilly, A.M. O'Hagan, G. Dalton, Attitudes and perceptions of fishermen on the island of Ireland towards the development of marine renewable energy projects, Mar. Policy 58 (2015) 88–97, https://doi.org/10.1016/j.marpol.2015.04.001.

[10] K. Reilly, A.M. O'Hagan, G. Dalton, Moving from consultation to participation: a case study of the involvement of fishermen in decisions relating to marine renewable energy projects on the island of Ireland, Ocean & Coastal Management 134 (2016) 30–40, https://doi.org/10.1016/j.ocecoaman.2016.09.030.

[11] P. Bonar, I. Bryden, A. Borthwick, Social and ecological impacts of marine energy development, Renew. Sust. Energ. Rev. 47 (2015) 486–495.

[12] S.J. Dreyer, H.J. Polis, L.D. Jenkins, Changing tides: acceptability, support, and perceptions of tidal energy in the United States, Energy Res. Soc. Sci. 29 (2017) 72–83, https://doi.org/10.1016/j.erss.2017.04.013.

[13] J. de Groot, I. Bailey, What drives attitudes towards marine renewable energy development in island communities in the UK? Int. J. Mar. Energy 13 (2016) 80–95.

[14] P. Devine-Wright, B. Wiersma, Understanding community acceptance of a potential offshore wind energy project in different locations: an island-based analysis of 'place-technology fit', Energy Policy 137 (2020) https://doi.org/10.1016/j.enpol.2019.111086.

[15] B. Sovacool, Rejecting renewables: the socio-technical impediments to renewable electricity in the United States, Energy Policy 37 (11) (2009) 4500–4513.

[16] B.A. Israel, A.J. Schulz, E.A.E.A. Parker, Critical issues in developing and following community-based participatory research principles, in: Community-Based Participatory Research for Health, Jossey-Bass, San Francisco, 2008, pp. 47–62.

[17] J. Cavaye, Rural community development – new challenges and enduring dilemmas, J. Reg. Anal. Policy 31 (2) (2001) pp.

[18] I. Jayaweera, Livelihood and Diversification in Rural Coastal Communities, Stockholm Resilience Center, Stockholm, 2010. Dissertation.

[19] L. Jolliffe, R. Farnsworth, Seasonality in tourism employment: human resource challenges, Int. J. Contemp. Hosp. Manag. 15 (6) (2003) 312–316.

[20] R.M. Puertas Medina, J.M. Martín Martín, J.M. Guaita Martínez, P. Azevedoc Serdeira, Analysis of the role of innovation and efficiency in coastal destinations affected by tourism seasonality, J. Innov. Knowl. 7 (1) (2022).

[21] J. Lloret, A. Carreño, H. Carić, J. San, L.E. Fleming, Environmental and human health impacts of cruise tourism: a review, Mar. Pollut. Bull. 173 (2021).

[22] The economic impacts of marine debris on tourism-dependent communities, in: Marine Debris Program: Office of Response and Restoration, NOAA, 2022.

[23] E. English, C. Wagner, J. Holmes, The Effects of Marine Debris on Beach Recreation and Regional Economies in Four Coastal Communities: A Regional Pilot Study, in: Final Report, Marine Debris Devision, National Oceanic and Atmospheric Administration, 2019.

[24] R.A. Pielke Jr., The Honest Broker: Making Sense of Policy and Politics, Cambridge University Press, 2007.

[25] Initiative Gateway and Natural Amenity Research. n.d. "Boomtown: Amentiy Migration in the Rural West and the Rise of the "Zoom Town"." Utah State University.

[26] R. Leichenko, M. McDermott, E. Bezborodko, M. Brady, E. Namendorf, Economic vulnerability to climate change in coastal New Jersey: a stakeholder-based assessment, J. Extreme Events 1 (1) (2014). June 16.

[27] J. Mo, Tourism Dependency of Island and Developing Countries, Global Edge, 2018.

[28] R.A. Aljarallah, Natural resource dependency, institutional quality and human capital development in gulf countries, Heliyon 6 (7) (2020).

[29] G.M. Muhamad, A. Heshmati, N.T. Khayyat, How to reduce the degree of dependency on natural resources? Resour. Policy 72 (2021).

[30] G. Aldasoro-Saida, L.O. Lozanob, Marine resource dependence in rural coastal communities south of the reef corridor of the Southwest Gulf of Mexico, Ocean Coast. Manag. 211 (October 1 2021.).

[31] NOAA, What Threats do Coastal Communities Face?. https://oceanservice.noaa.gov/facts/coastalthreat.html#:∼:text=The%20threats%20to%20coastal%20communities,declarations%20is%20related%20to%20flooding.

[32] G. Kallis, P. Stephanides, E. Bailey, P. Devine-Wright, K. Chalvatzis, I. Bailey, The challenges of engaging island communities: lessons on renewable energy from a review of 17 case studies, Energy Research & Social Science 81 (November 2021).

[33] H. Dorotić, B. Doračić, V. Dobravec, T. Pukšec, G. Krajačić, N. Duić, Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources, Renew. Sust. Energ. Rev. 99 (January 2019) 109–124.

[34] T. Hodge, E. Fasching, Today in Energy: During 2021, U.S. retail electricity prices rose at fastest rate since 2008, Energy Information Agency, 2022.

[35] A. LiVecchi, et al., Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets, U.S Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, D.C., 2019.

[36] O. Serpell, Innovation in Isolation: Islands and the Energy Transition, in: Klienman Center for Energy Policy, University of Pennsylvania, 2020.

[37] M. Brown, C. Fassett, P. Whittle, J. Mcconnaughey, J. Lo, in: Storms batter aging power grid, including Maine's, as climate disasters spread, Press Herald, 2022.

[38] The Effects of Climate Change on Florida's Ocean and Coastal Resources. A Special Report to the Florida Energy and Climate Commission and the People of Florida, 2009. Tallahassee, FL.

[39] "Natural Hazards." The National Academies.n.d.

[40] Weather-related disasters increase over past 50 years, causing more damage but fewer deaths, WMO, 2021.

[41] R. Meyer, America is Being Pummeled by Disasters, The Atlantic, 2020.

[42] R.J. Pasch, R. Berg, D.P. Roberts, P.P. Papin, National Hurricane Center: Tropical Cyclone Report, NOAA, 2021.

[43] I. Ajzen, The theory of planned behavior, Organ. Behav. Hum. Decis. Process. 50 (2) (1991) 179–211.

[44] H. Boudet, Public perceptions of and responses to new energy technologies, Nat. Energy 4 (6) (2019) 446–455.

[45] N. Bronfman, R. Jimenez, P. Arevalo, Understanding social acceptance of electricity generation sources, Energy Policy 46 (2012) 246–252.

[46] E.De Luca, C. Nardi, L.Gaetana Giuffrida, M. Krug, M.R.Di Nucci, Explaining factors leading to community acceptance of wind energy. Results of an expert assessment, Energies 13 (8) (2020) 2119.

[47] P. Devine-Wright, Public engagement with large-scale renewable energy technologies: breaking the cycle of NIMBYism, WIREs Clim. Change 2 (1) (2011) 19–26.

[48] J. Dwyer, D. Bidwell, Chains of trust: energy justice, public engagement, and the first offshore wind farm in the United States, Energy Res. Soc. Sci. 47 (2019) 166–176.

[49] J. Firestone, C. Hirt, D. Bidwell, M. Gardner, J. Dwyer, Faring well in offshore wind power siting? Trust, engagement and process fairness in the United States, Energy Research & Social Science 62 (2020).

[50] N. Gupta, A. Fischer, L. Frewer, Socio-psychological determinants of public acceptance of technologies: a review, Public Underst. Sci. 21 (7) (2012) 782–795.

[51] N.M.A. Hujits, E.J.E.M.L. Steg, Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework, Renew. Sust. Energ. Rev. 16 (1) (2012) 525–531.

[52] A.M. Mayeda, A.D. Boyd, Factors influencing public perceptions of hydropower projects: a systematic literature review, Renew. Sust. Energ. Rev. 121 (2020).

[53] J. Rand, B. Hoen, Thirty years of North American wind energy acceptance research: what have we learned? Energy Res. Soc. Sci. 29 (2017) 135–148.

[54] S.H. Schwartz, Universals in the content and structure of values: theoretical advances and empirical tests in 20 countries, Adv. Exp. Soc. Psychol. 25 (1992) 1–65.

[55] P.C. Stern, T. Dietz, T.D. Abel, G. Guagnano, L. Kalof, A value-belief-norm theory of support for social movements: the case of environmentalism, Hum. Ecol. Rev. 6 (2) (1999) 81–97.

[56] A. Tabi, R. Wustenhagen, Keep it local and fish-friendly: social acceptance of hydropower projects in Switzerland, Renew. Sust. Energ. Rev. 68 (1) (2017) 763–773.

[57] M. Wolsink, Wind power and the NIMBY-myth: institutional capacity and the limited significance of public support, Renew. Energy 21 (1) (2000) 49–64.

[58] J. Zoellner, P. Schweizer-Ries, C. Wemheuer, Public acceptance of renewable energies: results from case studies in Germany, Energy Policy 36 (11) (2008) 4136–4141.

[59] Faroe Islands – tidal energy to reach 100% renewable by 2030, 2021.

[60] B. David, Combining flood damage mitigation with tidal energy generation: lowering the expense of storm surge barrier costs, Coast. Eng. 36 (2020).
[61] M. Alam, D. Bhatnagar, S. Bhattacharya, R. O'Neil, D. Preziuso, Understanding the Grid Value of Marine Renewable Energy: An Analytical Approach, 2019.
[62] D. Bhatnagar, et al., Grid Value Proposition of Marine Energy: A Preliminary Analysis, 2021.
[63] D.C. Preziuso, et al., Understanding the Grid Value Proposition of Marine Energy: A Literature Review, 2019.
[64] "Marine Energy & the Blue Economy," ed: Department of Energy.n.d.
[65] Hydropower Explained: Ocean Thermal Energy Conversion, U.S Energy Information Agency, 2021.
[66] L. Kilcher, M. Fogarty, M. Lawson, Marine Energy in the United States: An Overview of Opportunities, National Renewable Energy Laboratory, 2021.
[67] Open EI: Primre, National Renewable Energy Laboratory, 2022.
[68] J. Leijon, J. Forslund, K. Thomas, C. Boström, Marine current energy converters to power a reverse osmosis desalination plant, Energies 11 (2018) 2880.
[69] I. Dincer, M.F. Ezzat, Renewable Energy Production, Comprehensive Energy Systems, 2018.
[70] B. Cable, NAVFAC Ocean Thermal Energy Conversion (OTEC) Project; OTEC Technology Development Report, Defense Technical Information Center, 2010.
[71] S.M. Masutani, P.K. Takahashi, Ocean Thermal Energy Conversion (OTEC), Academic Press, Honolulu, 2001.
[72] F. Helfer, C. Lemckert, The power of salinity gradients: an Australian example, Renew. Sust. Energ. Rev. 50 (2015).
[73] E. Brauns, Towards a worldwide sustainable and simultaneous large-scale production of renewable energy and potable water through salinity gradient power by combining reversed electrodialysis and solar power? Desalination 219 (1–3) (2008) 312–323.
[74] K. Raub, K. Stepenuck, B. Panikkar, Exploring the food–energy–water nexus approach to enhance coastal community resilience research and planning, Glob. Sustain. 4 (e21) (2021).
[75] Y. Li, L. Willman, Feasibility analysis of offshore renewables penetrating local energy systems in remote oceanic areas – a case study of emissions from an electricity system with tidal power in southern Alaska, Appl. Energy 117 (15) (2014) 42–53.
[76] Australian Academy of Science. n.d. "Harnessing the Power of the Ocean." https://www.science.org.au/curious/technology-future/ocean-power.
[77] PNNL, Tidal Energy. https://www.pnnl.gov/explainer-articles/tidal-energy.
[78] "Comprehensive Renewable Energy Feasibility Study: Sitka, Alaska," n.d.
[79] K. Rose n.d. "Study Finds Wind Power is Sitka's 'Strongest Resource' for Future Energy Needs." Alaska Public Media, PBS, NPR. https://alaskapublic.org/2023/01/03/study-finds-wind-power-is-sitkas-strongest-resource-for-future-energy-needs/.
[80] N.K. Sather, Z. Yang, San Juan Islands Tidal Energy Characterization, 2022.
[81] OPALCO, Quick Fact: OPALCO Tidal Energy Pilot Project. https://www.opalco.com/quick-fact-opalco-tidal-energy-pilot-project/2022/11/.
[82] J. Heller, Powering an Alaska Village, Sitka, Alaska, HPB Magazine, 2018.
[83] Islands Climate Resilience, Working Toward Climate Resilience in the San Juan Islands, 2017. https://www.cakex.org/sites/default/files/documents/SJI_WorkingTowardClimateResilience_lowres.pdf.
[84] City of Sitka, Sitka's Energy Transition Journey. https://www.cityofsitka.com/news/post/16651/.
[85] D. Nicholls, T. Patterson, Community energy management in Sitka, Alaska: what strategies can help increase energy independence, in: General Technical Report PNW-GTR-882, Pacific Northwest Research Station, 2013.
[86] OPALCO n.d. "Decatur Island Microgrid Project." Orcas Power & Light Co-Op. https://www.opalco.com/save/community-solar/decatur-island-microgrid-project/.
[87] "QuickFacts: Sitka city and borough, Alaska," n.d.ed: U.S Census Bureau.
[88] About Us, Sitka Tribe of Alaska, 2011.
[89] "Data USA: Sitka, AK," n.d. ed: Deloitte and Datawheel.
[90] "About Sitka," ed: City & Borough of Sitka Alaska.n.d.
[91] Sitka: Climate Change, National Parks Service, 2019.
[92] The Future of Energy in Sitka, Sitka Conservation Society, Sitka, 2012. Dissertation.
[93] "Southeast Alaska Integrated Resource Plan," Alaska Energy Authority, 2012.
[94] A. Solano, Technical Assistance for CBS Utility Planning, in: Presented at the Energy Transitions Initiative Partnership Project U.S. Department of Energy, 2022.
[95] "Lime Kiln Point State Park," ed: Washington State Parks.n.d.
[96] Official Travel Site San Juans, Washington, San Juans Visitors Bureau, 2022.
[97] A. Vance-Sherman, San Juan county profile, in: Employment Security Department, ed, Washington State, 2022.
[98] G. Dolson, Energy Resilience in an Archipelago, HDR Inc, 2019.
[99] "Battery Energy Storage Pairs with Solar Energy to Bring Independence and Reliability to a Remote Archipelago," ed: HDR Inc.n.d.
[100] H. Spaulding, New thinking, new technology needed for 'transformation' to a greener future, in: Salish Current, 2020.
[101] M. Yañez-Barnuevo, J.-M. Cross, ElectrificationEnergy EfficiencyEnergy Transmission and StorageRural Development Washington State Islands Work Towards a Fossil-Fuel-Free Future, Environmental and Energy Study Institute, 2020.
[102] Justice40: A Whole-of-Government Initiative, The White House, 2022.
[103] L. Jason, D. Glenwick, Handbook of Methodological Approaches to Community-based Research: Qualitative, Quantitative, and Mixed Methods, Oxford University Press, 2016.
[104] D.D. Whitney, A. Trosten-Bloom, The Power of Appreciative Inquiry: A Practical Guide to Positive Change, Berrett-Koehler Publishers, 2010.
[105] A.M. Kiember-Emmons, et al., A novel mixed methods approach combining geospatial mapping and qualitative inquiry to identify multilevel policy targets: the focused rapid assessment process (fRAP) applied to cancer survivorship, J. Mixed Methods Res. 16 (2) (2022) 183–206.
[106] J. Ervin, Rapid assessment of protected area management effectiveness in four countries, Bioscience 53 (9) (2003) 833–841.
[107] G.G. Singh, et al., A rapid assessment of co-benefits and trade-offs among sustainable development goals, Mar. Policy 93 (2018) 223–231.
[108] M. Orosz, Q. Altes-Buch, A. Mueller, V. Lemort, Experimental validation of an electrical and thermal energy demand model for rapid assessment of rural health centers in sub-saharan Africa, Appl. Energy 218 (2018) 382–390.
[109] M.B. Miles, M. Huberman, Qualitative Data Analysis: An Expanded Sourcebook, SAGE, 1994.
[110] J. Saldaña, The Coding Manual for Qualitative Researchers, SAGE, 2015.
[111] J.R. Campbell, Participatory rural appraisal as qualitative research: distinguishing methodological issues from participatory claims, Hum. Organ. 60 (4) (2001) 380–389.
[112] C. Butler, K.A. Parkhill, P. Luzecka, Rethinking energy demand governance: exploring impact beyond 'energy' policy, Energy Res. Soc. Sci. 36 (February 2018) 70–78.
[113] D. Bessette, et al., Energy democracy in practice: centering energy sovereignty in rural communities and Tribal Nations, in: Routledge Handbook of Energy Democracy, Routledge, London, 2021.
[114] L. Ewing, R.E. Flick, C.E. Synolakis, A review of coastal community vulnerabilities toward resilience benefits from disaster reduction measures, Environmental Hazards 9 (3) (September 2010) 222–232.
[115] C.S. Holling, G.K. Meffe, Command and control and the pathology of natural resource management, Conserv. Biol. 10 (2) (1996) 328–337.
[116] Z. Yang, T. Wang, R. Branch, M. Deb, Tidal stream energy resource characterization in the Salish Sea, Renew. Energy 172 (2021) 188–208.
[117] Bhattacharya SPS, B. Robertson, S. Hanif, M.J. Alam, D. Bhatnagar, D. Preziuso, R. O'Neil, Timing value of marine renewable energy resources for potential grid applications, Applied Energy 299 (2021) 117–281.
[118] T.G. Safford, M. Henly, J.D. Ulrich-Schad, K. Perkins, Charting a future course for development: natural resources, conservation, and community character in coastal Alaska, J. Rural CommunityDev. 9 (3) (2014) 21–41.
[119] J.D. Ulrich-Schad, P.M. Jakus, M. Bordigioni, D.E. Albrecht, Preferences for economic and environmental goals in rural community development in the Western United States, Rural. Sociol. 87 (2) (2022) 605–641.
[120] Z. Hashin, A. Rotem, A cumulative damage theory of fatigue failure, Mater. Sci. Eng. 34 (2) (1978) 147–160.