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1 Engineering for Change
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NREL is a national laboratory of the U.S. Department of Energy
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List of Acronyms

CDR	carbon dioxide removal
CO_2	carbon dioxide
EMEC	European Marine Energy Centre
GW	gigawatt
kg	kilogram
mCDR	marine carbon dioxide removal
MMT	million metric tons
NASEM	National Academies of Sciences, Engineering, and Medicine
NOx	nitrogen oxides
TRL	technology readiness level
TW	terawatt
UUV	unmanned underwater vehicle

Executive Summary

This report examines the application of marine energy for two distinct research areas, green hydrogen and marine carbon dioxide removal (mCDR). This evaluation considered the potential synergies between these sectors and marine energy, market maturity, barriers to adoption, policy enablers, and sustainability perspectives to help evaluate how marine energy could contribute to the power needs of these sectors as they grow. Through desk research and interviews with a diverse range of subject matter experts from academia, government, industry, venture capital, and nonprofits, these emergent sectors were identified as the most promising new opportunities for marine energy integration beyond those explored in the 2019 Powering the Blue Economy™ report.

Green hydrogen, produced in a sustainable manner, is increasingly being recognized as a key player in the global energy paradigm shift. Marine energy, with its distinguishing features such as high power density and the possibility of colocation with green hydrogen at sea, represents a viable strategy for powering green hydrogen generation. Despite the launch of several trailblazing global projects demonstrating the viability of integrating marine energy into green hydrogen production, several impediments remain, including investment prospects, lengthy permitting timelines, and potential environmental/social disruption. To mitigate these risks, a multi-pronged approach that includes strong policy support, technological innovation, stakeholder engagement, and rigorous impact analysis is required.

Oceans serve as critical sources of carbon sequestration platforms which mCDR, via various biological, chemical, or hybrid methods, leverage to accelerate carbon storage. For successful mCDR project implementation, stakeholders emphasize community involvement, equitable practices, and benefits distribution, as well as the need for policy enablers such as established regulatory frameworks and financial incentives. However, technical, societal, and environmental obstacles remain, necessitating additional research and development. This area of research is still developing, so less is known about the barriers to commercialization. Marine energy's ability to be colocated is promising to encourage its intersection with mCDR technologies, but more research, policy support, and pilot projects are needed.

In summary, the integration of marine energy with green hydrogen and/or carbon removal offers enticing prospects for long-term development. Realizing these opportunities, however, necessitates a nuanced understanding of potential challenges as well as a comprehensive risk and conflict mitigation strategy. To maximize these opportunities and successfully navigate the inherent complexities, a collaborative approach involving policymakers, stakeholders, and the scientific community is required.

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1 Green Hydrogen

1.1 Background

Hydrogen, specifically green hydrogen, which is produced with renewable energy, has become a vital component in the global energy transition due to its high energy content by weight, energy storage and delivery capabilities, and potential for decarbonizing sectors and applications (U.S. Energy Information Administration 2023). While fossil fuels contribute to more than 95% of hydrogen production, emergent technologies aim for reduced or zero emissions during production (Kobina and Gil 2022; Ocean Energy Europe 2021). To classify these means for production (summarized in Table 1), the industry uses color codes, separating those with high carbon footprints (such as black/brown and gray hydrogen) from the more environmentally friendly variants (like green, blue, turquoise, white, and pink hydrogen) (Deloitte 2023).

Clean hydrogen encompasses both green hydrogen and blue hydrogen. Both categories use methodologies such as electrolysis or thermochemical processes to split water into its basic components: hydrogen and oxygen. Separation occurs when an electric current flows through the water, causing the hydrogen atoms to detach from the oxygen atoms. The resulting hydrogen gas is gathered and stored for future use (Pilkington 2022). To generate electricity for electrolysis, green hydrogen uses renewable energy sources such as solar or wind, and blue hydrogen uses natural gas in tandem with carbon capture and storage.

Table 1. Hydrogen Classification (summarized from Deloitte (2023))

Hydrogen Classification	Description	Carbon Footprint
Black/Brown	Produced using the gasification of coal	High
Gray	Produced through natural gas reforming	Medium
White	Hydrogen extracted from underground wells through drilling	Medium
Turquoise	Produced through pyrolysis of natural gas	Medium
Blue	Produced from natural gas and coal but includes carbon capture and storage	Low
Green	Produced using renewable energy	Neutral
Pink	Produced via nuclear energy	Neutral

While the green hydrogen market is still in a developmental phase, its growth potential is significant, and it is predicted by some estimates to meet up to 15%–30% of the world's energy needs by 2050 (Deloitte 2023). For the United States, the 2023 U.S. National Clean Hydrogen Strategy and Roadmap details clean hydrogen decarbonization pathways and anticipates a marked rise in clean hydrogen production (Hydrogen and Fuel Cell Technologies Office n.d.).

Although clean hydrogen production is virtually nonexistent now, there is a vision to elevate clean hydrogen production to 10 million metric tons (MMT) annually by 2030, 20 MMT by 2040, and 50 MMT by 2050. These ambitious targets are based on anticipated demand in sectors where hydrogen can be economically viable, such as industrial applications, heavy-duty transportation, and long-term energy storage. In alignment with the U.S. long-term climate strategy (White House 2021), using clean hydrogen can potentially reduce U.S. emissions by roughly 10% by 2050 compared to 2005 (Hydrogen and Fuel Cell Technologies Office n.d.). Additionally, an independent review of the U.S. Department of Energy's *Pathways to Commercial Liftoff: Clean Hydrogen* report suggests that the expanding hydrogen economy might pave the way for an influx of 100,000 direct and indirect jobs by 2030 (U.S. Department of Energy 2023). This growth is attributed to the launch of new capital endeavors and the establishment of clean hydrogen infrastructure.

Currently, electrolyzer technology for green hydrogen production ranges from technology readiness level (TRL) 6 to TRL 9. More mature technologies (e.g., alkaline and proton exchange membranes) are commercially available, though they require more policy support to compete with traditional hydrogen production methods. Total electrolyzer installed capacity was expected to reach nearly 3 gigawatts (GW) by the end of 2023, with capacity scaling to 170–365 GW by 2030 if current projects in the pipeline are fully realized (International Energy Agency n.d.). The current cost for green hydrogen production is \$3–\$8 per kilogram (kg) (given in U.S. dollars; in contrast to gray hydrogen which is \$1–\$2/kg) (PwC n.d.). However, a 2021 report by the Rocky Mountain Institute predicts that the cost for green hydrogen production could fall below \$2/kg by 2026, with reductions in the cost of electrolyzers driving costs down (Rocky Mountain Institute 2021).

1.2 Energy and Resources Required for Green Hydrogen Production

Meeting the power needs for green hydrogen is a significant undertaking. To meet just 10% of expected global primary energy consumption by 2050, a massive 670 MMT of hydrogen will be required. This translates to a demand for approximately 26,500 terawatt-hours of electricity—nearly the amount of all global electricity generated in 2020. Solely depending on renewable sources to meet this demand and decarbonize the grid would necessitate an eightfold increase in the global renewable capacity of 2020, adding up to nearly 23 terawatts (TW). While the International Energy Agency recorded the highest addition of renewable capacity in 2020 (0.28 TW), achieving an additional 23 TW of capacity at this rate would require nearly eight decades. Moreover, given the variable nature of sources like solar and wind, substantial energy storage solutions would be imperative to maintain consistent power availability (DiElsi 2023).

In addition to energy requirements, the resources and materials for green hydrogen production are similarly vast. Electrolysis, pivotal for hydrogen production, would require about 1.6 trillion gallons of water annually if green hydrogen were to provide 10% of 2050's global energy. Electrolysis requires high-quality water, potentially implying more water treatment facilities and escalating both capital costs and electricity consumption. Furthermore, the manufacturing of electrolyzers requires specific materials, and resources are needed for the compression, storage, and transportation of hydrogen, especially when it is used away from its production site, further complicating the process (DiElsi 2023).

1.3 Potential for Marine Energy and Green Hydrogen Integration

Amid these growing energy and resource needs, marine energy has surfaced as a promising strategy for green hydrogen generation and for addressing energy storage and transportation issues. The application of marine energy for green hydrogen production and use was mentioned in stakeholder interviews on potential applications where marine energy could support power needs and is the subject of ongoing exploration from NREL. Marine energy could be used as a complementary renewable energy source when solar and wind resources are unavailable, allowing for increased electrolyzer use, increasing the overall efficiency of green hydrogen production while driving costs down. The 2022 NREL report *Unlocking the Potential of Marine Energy Using Hydrogen Generation Technologies* outlines multiple other applications for this synergy in the realm of the blue economy (Thorson et al. 2022).

Firstly, ocean observation and navigation tools, vital for oceanographic monitoring and ensuring safe navigation, could benefit significantly from a combined marine energy-green hydrogen system. These tools range from small buoys to extensive offshore platforms. The use of marine energy sourced from waves and ocean currents coupled with hydrogen storage has the potential to extend operational durations and improve safety by limiting required human intervention in comparison to conventional batteries.

Secondly, the marine transportation sector, a notable contributor to global emissions, is being transformed with the introduction of cleaner fuels, electric vessels, and hydrogen fuel cells. Here, marine energy combined with hydrogen systems holds the potential to address a substantial portion of marine transport energy needs. For instance, while battery-electric vessels are suited for shorter voyages, hydrogen-based systems have emerged as a promising solution for long-haul and heavy-duty maritime transit (Rocky Mountain Institute 2023). In addition, ocean thermal energy conversion systems, boasting consistent energy output, can be coupled with hydrogen production, offering a cleaner alternative to conventional fossil fuels for long-duration sea journeys.

Recent announcements from major international shipping carriers provide more context for potential timelines to realize green-hydrogen-powered vessels and ports. In 2022, the Joint Statement on Green Hydrogen and Green Shipping (Rocky Mountain Institute 2023) set targets for:

- “Achieving commercially viable zero-emissions vessels operating on the deep sea by 2030”
- “Scaling up production of green hydrogen to 5.5 million tons per year by 2030 for use in shipping”
- “Full decarbonization of the shipping sector by 2050 at the latest.”

Additionally, at COP28, Namibia announced plans for developing Green Corridors through their Green Hydrogen Program and the Mærsk McKinney Møller Center for Zero Carbon Shipping (Ocean Panel 2023).

Lastly, the rapidly expanding domain of unmanned underwater vehicles (UUVs), which are primarily battery-dependent, can greatly benefit from marine energy and hydrogen. With ocean current turbines and hydrogen systems, users can achieve longer UUV operational times, more comprehensive data collection, and reduced recharging frequency. Similarly, remote communities like areas of Alaska and island territories, which largely depend on diesel generators, can achieve energy independence and resilience through marine energy and hydrogen systems. Such systems not only present a viable alternative to the challenges posed by the conventional energy supply chain but also offer cost and environmental advantages (Thorson et al. 2022).

1.4 Green Hydrogen Projects

1.4.1 Marine Energy and Green Hydrogen

Pioneering projects across the globe are leveraging marine energy resources, including wave and tidal energy, for green hydrogen production. In South Korea, the Yongsoo oscillating water column wave energy converter at the Korea Research Institute of Ships and Ocean Engineering wave energy test site on Jeju Island is set to produce green hydrogen (Garanovic 2023). In the United States, Panthalassa just recently began prototyping the next generation of their buoy, designed to convert wave energy into green hydrogen (Vargas 2024).

Namibia is also integrating marine energy into green hydrogen production, as demonstrated by the collaboration between Finnish wave energy technology developer AW-Energy Oy and Namibian company Kaoko Green Energy Solutions. The project plans to harness wave energy for desalination and green hydrogen production (Hydro Review 2023). Similarly, in the UK, Marine Power Systems and Marine2o are developing integrated solutions for the production and transportation of green hydrogen using marine vessels, harnessing the potential of floating wind and wave energy (Ocean Energy Europe 2021).

The European Marine Energy Centre (EMEC) is also demonstrating leadership in marine energy and green hydrogen innovation with its comprehensive hydrogen R&D ecosystem that aims to demonstrate the full value chain of hydrogen production, storage, transportation, and end use. In 2017, EMEC successfully produced the first hydrogen generated from tidal power, harnessing energy from clients testing their devices at the site (EMEC n.d.). In 2020, Orbital Marine Power and Invinity Energy Systems received funding from the European Union’s Horizon 2020 research and innovation program to spearhead the FORWARD2030 project at EMEC, which will integrate a tidal stream turbine with a hydrogen production facility. The project aims to deploy 2.030 megawatts of tidal energy by 2030 and use the electricity generated by tidal turbines to power EMEC’s hydrogen production plant (Forward 2030 n.d.; Garanovic 2022). Such projects highlight the substantial opportunity for integrating marine energy into green hydrogen production.

1.4.2 Offshore Wind Energy and Green Hydrogen

Outside of marine energy, there are several green hydrogen-offshore wind projects that are underway. In the Netherlands, the FlexH2 project intends to develop and demonstrate the technology to accelerate the scale-up of offshore wind to green hydrogen production (FlexH2 n.d.). Japan’s largest hydrogen plant powered by offshore wind energy is set to open by March 2024 in Hokkaido. It aims to produce 550 tons of hydrogen annually, fueling more than 10,000 hydrogen vehicles as well as data centers, port cargo equipment, and refrigerated warehouses. Participants include Hokkaido Electric Power, Green Power Investment, Nippon Steel Engineering, and Air Water (Mukano 2021). In November 2023, RWE and Hyundai Engineering

& Construction signed a memorandum of understanding to develop offshore wind and green hydrogen. The project aims to increase South Korea's renewable energy capacity to 108.3 GW by 2036, including 34.1 GW from wind energy, of which 24 GW will be offshore (Memija 2023).

1.4.3 Desalination and Green Hydrogen

The integration of desalination with hydrogen production is an emerging field that has experienced notable advancements and pilot demonstrations. For instance, researchers in China have established a combined desalination-electrolysis system to produce green hydrogen directly from seawater, using evaporation within an electrochemical cell to purify the seawater, subsequently facilitating direct seawater electrolysis. This innovative system circumvents the challenges presented by chloride ions, which have traditionally led to corrosion and inefficiencies in electrolysis. A demonstrative unit in Shenzhen Bay successfully operated for 133 days, producing over a million liters of hydrogen without encountering issues like corrosion or heightened impurity levels (Atkinson 2022; Xie et al. 2022). Concurrently, collaborations between companies in the United States and the Netherlands have resulted in scalable systems that combine desalination with green hydrogen production using renewable energy sources such as solar and wind. This integration leverages the waste heat from the electrolysis process to power desalination, highlighting its environmental efficacy (Kennedy 2023). Moreover, a significant project in Neom, Saudi Arabia, in collaboration with Air Products and ACWA Power, underscores the feasibility of this integration on a large scale. A desalination plant, set to meet 30% of the city's projected water demand by 2025, will be entirely powered by green hydrogen, illustrating the synergy between desalination and hydrogen production at an industrial scale (Aquatech Trade 2022; NEOM 2022).

1.5 Barriers for Marine Energy-Green Hydrogen Systems

The journey toward integrated marine energy-green hydrogen systems must still address several commercial barriers. For marine energy, some investors are waiting until the technology is at a higher TRL and able to provide affordable and reliable energy within a viable commercial framework before considering adding it to their portfolios. Marine energy projects also face poor perceptions from failed investments in years past and comparisons to solar and wind for price expectations. Marine energy projects require investors who are willing to take on multi-million-dollar risk and can help projects navigate the "valley of death" commonly faced by startups.

For green hydrogen, projections are optimistic given the level of investment at the national and international levels. However, green hydrogen faces barriers related to developing new codes and standards, navigating complex supply chains, and considering infrastructure and logistics costs. Combined marine energy-green hydrogen systems will need to be able to meet a price point that consumers can bear, which is dependent on deployability, scale, operational profiles, and cost of implementation, all of which are very context-specific.

As with many onshore and offshore projects, permitting remains a barrier to implementation and needs to be streamlined, similar to what was done for the oil and gas industry. In the United States, clear processes for securing federal lease rights and project permitting would be beneficial. Internationally, permitting requirements are highly country-specific, and it can be unclear which authority to engage with. Some of these challenges can be circumvented by strategically pursuing projects alongside ports or other existing infrastructure. Additionally, permitting and licensing can be time- and cost-intensive; in some cases, can cost millions of dollars, making smaller marine energy projects uneconomical. Currently, Ocean Energy Europe is focusing on standardizing permitting and licensing for offshore processes to streamline project development (Ocean Energy Europe 2020).

Finally, many barriers remain to using green hydrogen (or other renewables) as a fuel for marine vessels. Our interviews indicate that shipping vessels that travel into international waters are typically at least 1,500 nautical miles from shore. As a result, most shipboard infrastructure relies on marine fuel oil. Although nuclear fuel has been touted as a possible “clean” alternative, renewables and other clean energy alternatives are not being actively considered by most major international shipping companies.

1.6 Sustainability Considerations for Marine Energy and Green Hydrogen

While green hydrogen has a role in the overall energy transition, concerns remain around its social, economic, and environmental sustainability. These challenges include harmful byproducts, health and public safety, resource intensity, and overall unknown potential ecosystem and social disruption (Energy Innovation 2022; Thorson et al. 2022).

Hydrogen is a small molecule that is both colorless and odorless. As companies pursue hydrogen mixing using existing infrastructure, there are concerns around pipeline leakage/breakage and explosions, with additional public safety concerns if used in residential settings. Hydrogen leakage would also be detrimental to the environment, as it has a global warming potential nearly 6 times higher than carbon dioxide (CO_2) over a 100-year time horizon (Derwent et al. 2006).

While green hydrogen’s combustion is devoid of CO_2 emissions, it is not entirely environmentally benign. Combustion of hydrogen in the presence of air results in nitrogen oxides (NOx) generation, in contrast to hydrogen fuel cells, which do not form harmful byproducts. Notably, burning hydrogen can lead to NOx emissions more than 50% higher than natural gas due to high flame temperatures (DiElsi 2023). Strategies exist to reduce NOx emissions, such as optimizing combustion conditions, but could affect output efficiency and NOx after-treatment (Lewis 2021). In addition to contributing to global warming, high concentrations of NOx can lead to acute and chronic illnesses such as respiratory irritation/infection and asthma (Environmental Protection Agency 2023). In the United States, racial/ethnic minorities and those of lower socioeconomic status are disproportionately impacted by higher NOx concentrations (Nunez et al. 2024), and environmental justice advocates worry that the shift to a hydrogen economy will only exacerbate these disparities (Energy Innovation 2022).

Additionally, while electrolysis to produce hydrogen primarily emits gaseous oxygen, when seawater undergoes electrolysis, it can produce chlorine gas, a hazardous waste that requires careful disposal. Despite these challenges, marine energy-hydrogen systems offer a unique advantage: the ability to capture and use the byproduct oxygen in subsea applications where oxygen is scarce. Moreover, the produced chlorine gas could be repurposed to address biofouling in marine settings. However, a critical hurdle lies in determining economically viable uses for these valuable byproducts, ensuring both hydrogen and its byproducts are beneficial. Evaluating the feasibility of marine energy-hydrogen systems involves comparing the value of the byproduct to its associated capture and transportation costs.

Furthermore, marine energy-hydrogen systems can be disruptive to marine ecosystems. Heavy equipment operations might cause disturbances ranging from acoustic to biological. Appropriate mitigation strategies are essential to safeguard sensitive marine ecologies (Thorson et al. 2022).

Lastly, where significant maritime space is required for marine energy-green hydrogen projects, access to food, water rights, and territorial sovereignty may be jeopardized for communities with high socioeconomic vulnerabilities, potentially resulting in social displacement (Brannstrom and Gorayeb 2022). When inequitable power structures are replicated, even in renewable energy projects, vulnerable communities, such as Indigenous or historically marginalized groups, may continue to be disproportionately burdened without receiving equal benefits compared to other stakeholders (Brannstrom and Gorayeb 2022).

The Inter-American Development Bank recently released a scoping study assessing potential social, economic, and environmental risks from green hydrogen production in Latin America and the Caribbean. The Inter-American Development Bank highlights potential worker safety hazards (hydrogen is highly flammable, and the generation process involves the operation of complex, high-pressure equipment). For similar reasons, local communities could also be at risk from leaks and explosions during hydrogen storage and transport. Green hydrogen production could also exacerbate existing water shortages due to the large quantities of water consumed during the generation process. Finally, waste byproducts from the generation of ammonia and methanol could lead to the contamination of local water and soil (Signoria and Barlettan 2023).

To mitigate some of the negative impacts of marine energy projects, researchers at Vanderbilt University and Sandia National Laboratories have developed a list of guiding questions to consider in what they call “meaningful marine renewable energy development.” These guiding questions evaluate marine energy across all the phases of project development to consider 1) people, housing, and livelihood; 2) community engagement; 3) culture, land, and water; and 4) infrastructure and environmental impact (Caballero, Gunda, and McDonald 2023).

1.7 Opportunities for Marine Energy and Green Hydrogen

The previously discussed potential barriers highlight opportunities for additional support to de-risk marine energy and green hydrogen ventures. Support could include:

- Researching and developing solutions for current technological challenges, funding pilot projects and full-scale deployments
- Providing more lenient and proactive debt funding
- Providing permitting and licensing support through case studies
- Monitoring potential ecosystem disruption
- Engaging with communities and other stakeholders to mitigate potential inequitable socioeconomic outcomes.

Recent upticks in marine energy-green hydrogen pilot projects signal growing interest, making it an appealing area for further investigation and support (Table 2).

Table 2. Opportunities for Marine Energy in Green Hydrogen Operations

Operational Process	Description
Production/generation conversion process	Benefits of coupling marine energy-green hydrogen systems include higher energy reliability at both short and long timescales, greater electrolyzer utilization, higher energy density, safety, and potential for colocating at sea.
Production/clean water	Leveraging marine energy for desalination plants to produce purified water as an input to green hydrogen production.
Transport	Using wave energy to power transportation of green hydrogen via marine vessels.
Monitoring/ecology	Marine energy can be used to monitor potential ecosystem disruption associated with green hydrogen production.

2 Marine Carbon Dioxide Removal

The urgency of climate change has placed oceans at the forefront of carbon drawdown strategies. With their vastness and untapped potential, oceans offer various mechanisms for carbon removal through biological approaches (e.g., seaweed cultivation for carbon sequestration), chemical approaches (e.g., ocean alkalinity enhancement), or hybrid methods (e.g., direct ocean capture using electrochemical techniques) (Ocean Visions 2023). This interest is fueled by the continual growth of atmospheric CO_2 and its resulting impact on climate change and ocean acidification (National Academies of Sciences, Engineering, and Medicine [NASEM] 2022).

Stakeholders play a significant role in carbon removal efforts, with their considerations encompassing community involvement, equity, and the fair distribution of benefits, particularly for coastal communities and marginalized groups. Public engagement, legal safeguards, and interdisciplinary approaches involving stakeholders such as ocean conservation organizations, technology firms, and research institutes are key to the success of carbon removal efforts. Cross-sectoral marine governance, with strong state support and partnerships, offers effective governance opportunities (Boettcher et al. 2021; NASEM 2019).

Policy enablers, including robust legal, regulatory, and policy frameworks, are vital for the successful implementation and scaling up of carbon dioxide removal (CDR) projects. The presence of financial incentive policies such as carbon pricing, grants, and market mechanisms, coupled with an effective policy design that considers equity, adaptation, and environmental factors, are critical to support diverse CDR approaches and ensure the achievement of environmental and societal goals (NASEM 2022). Examples of these include the Energy Act of 2020 and the 45Q tax credit carbon capture program in the United States. However, broader financial incentive policies, including carbon pricing, grants, standards, co-benefit policies, and other market mechanisms, are necessary to support diverse CDR approaches (NASEM 2022).

While the opportunities are exciting, it is essential to recognize the technical, societal, and environmental barriers that carbon removal projects face. Technically, the choice of marine CDR (mCDR) approaches, including natural systems, enhanced natural systems, and mechanical/chemical processes, raises concerns about measurability and ecosystem disturbance that should be further explored. Research and development are crucial for lowering technical barriers and measuring impact, yet large-scale mCDR technologies face substantial certification challenges that must be overcome as well (NASEM 2022). From a sustainability perspective, carbon capture technologies have been criticized for delaying actions to mitigate carbon emissions in the first place, perpetuating environmental inequalities, and potentially displacing coastal communities if not approached with care (NASEM 2022; Boettcher et al. 2021).

One mitigation strategy to avoid potential conflict between those who use marine resources (e.g., mCDR technology deployers, fishers, aquaculturists, tourism groups) is to deploy marine spatial planning, which uses public processes to "[analyze and allocate] the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process" (Boettcher et al. 2021; Intergovernmental Oceanographic Commission of UNESCO 2023; Pennino et al. 2021). However, where financial benefits, such as carbon credits and investment capital, skew toward those with more power (e.g., technology owners), local communities may not realize the same degree of benefits (Cooley et al. 2023). Community engagement and context are extremely important in assessing possible scenarios.

Social and environmental justice considerations become even more important when evaluating the scalability of mCDR technologies. Only certain mCDR technologies (e.g., ocean alkalinity enhancement and electrochemical processes) have a high potential for CO_2 removal (NASEM 2022). Furthermore, many other mCDR techniques could interact with existing ocean uses or ecosystems in ways that are not fully understood. For example, researchers highlight the potential of toxicity or other ecosystem impacts from mineral addition for ocean alkalinity enhancement. The greater the scale of mCDR deployment, the larger the impact (Cooley et al. 2023).

Many of the impacts of mCDR have been studied at a global scale, potentially omitting the types of local impact that would be significant for environmental justice outcomes. For example, the intensified infrastructure required for large-scale marine alkalinization will likely require colocation of mCDR with existing ancillary industries (such as brine management for desalination). As a result, mCDR could potentially intensify local environmental impacts from these industries (Lezaun 2021).

Despite some of these challenges, marine energy has emerged as an attractive alternative for powering mCDR and was mentioned as one potential application for integration with marine energy in several interviews ranging from the U.S. Department of Energy, academia, venture capital organizations, ocean foundations, and tech companies. Applications of marine energy for mCDR range from powering aquaculture systems (e.g., seaweed, macroalgae) and coastal restoration projects, as highlighted in various case studies (Rose and Ertsgaard 2023; Slegers et al. 2021; Nilsson et al. 2022) to energy-intensive electrochemical technologies, although these are at a more nascent stage (Table 3) (NASEM 2022).

At the current stage of development, marine energy and mCDR technologies could benefit from additional research and development support to overcome technical challenges, funding pilot projects and full-scale deployments illustrating potential to scale, and government level policy support. Additionally, research that supports the monitoring and evaluation of these emerging technologies to assess impact and potential ecosystem disturbances is necessary.

Table 3. Opportunities for Marine Energy in Marine Carbon Dioxide Removal

Process	Description
Biological carbon sequestration	Marine energy can power aquaculture systems with species such as seaweed or microalgae both near and offshore.
Pumping	Carbon embedded in aquaculture can be sequestered by burial at sea through artificial downwelling. One method for inducing downwelling is through pumps, which could be powered by marine energy.
Direct ocean capture	Marine energy could be used to power energy-intensive operations such as electrochemical or chemical processes that extract carbon from seawater; the carbon can then be stored and repurposed or reinjected back into the ground.
Monitoring	Marine energy could be used in the monitoring of ecology around areas of carbon sequestration or seaweed/algae farms.

3 Summary Matrix

🟩 Low Barrier 🟨 Intermediate Barrier 🟥 High Barrier	**Green Hydrogen**	**Marine Carbon Dioxide Removal (mCDR)**
Market Maturity	🟨 Pre-commercialization stage; significant anticipated growth in coming years; numerous pilot projects in development	🟨 mCDR still nascent
Marine Energy Attractiveness	🟩 Well suited due to high power density, potential for colocating; system coupling benefits include higher energy reliability, higher energy density, and safety	🟩 Opportunities for integration with aquaculture systems (e.g., seaweed, macroalgae), coastal restoration, and energy intensive electrochemical technologies
Enablers	🟩 Climate commitments; national roadmaps	🟩 Climate commitments; carbon utilization (aviation, concrete, etc.)
Barriers	🟨 Permitting and licensing; unknown costs for hybrid systems; byproduct generation; timeline for infrastructure development	🟨 More research and development needed; approaches for assessment and tracking of carbon removal and potential ecosystem disruption; difficulty scaling; simplified framework for permitting and licensing
Sustainability	🟨 Pros: Part of energy transition Cons: Generation of harmful byproducts; unknown ecosystem disruption; potential social displacement and socioenvironmental vulnerabilities	🟨 Pros: Helps to buy time to meet reductions requirements; coastal restoration Cons: Concerns around community engagement and distribution of benefits; potential ecosystem disruption and uncertainty
Stakeholders	🟩 Island and remote communities; shipping industry/ports; desalination orgs, utilities/existing infrastructure	🟨 Coastal communities, conservation groups, orgs developing ocean sensing and monitoring technologies, oceanic research institutes, desalination orgs, utilities/existing infrastructure
Synergies	🟩 Marine transport, aquaculture, UUVs, and monitoring	🟨 Marine transportation and UUV for monitoring

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